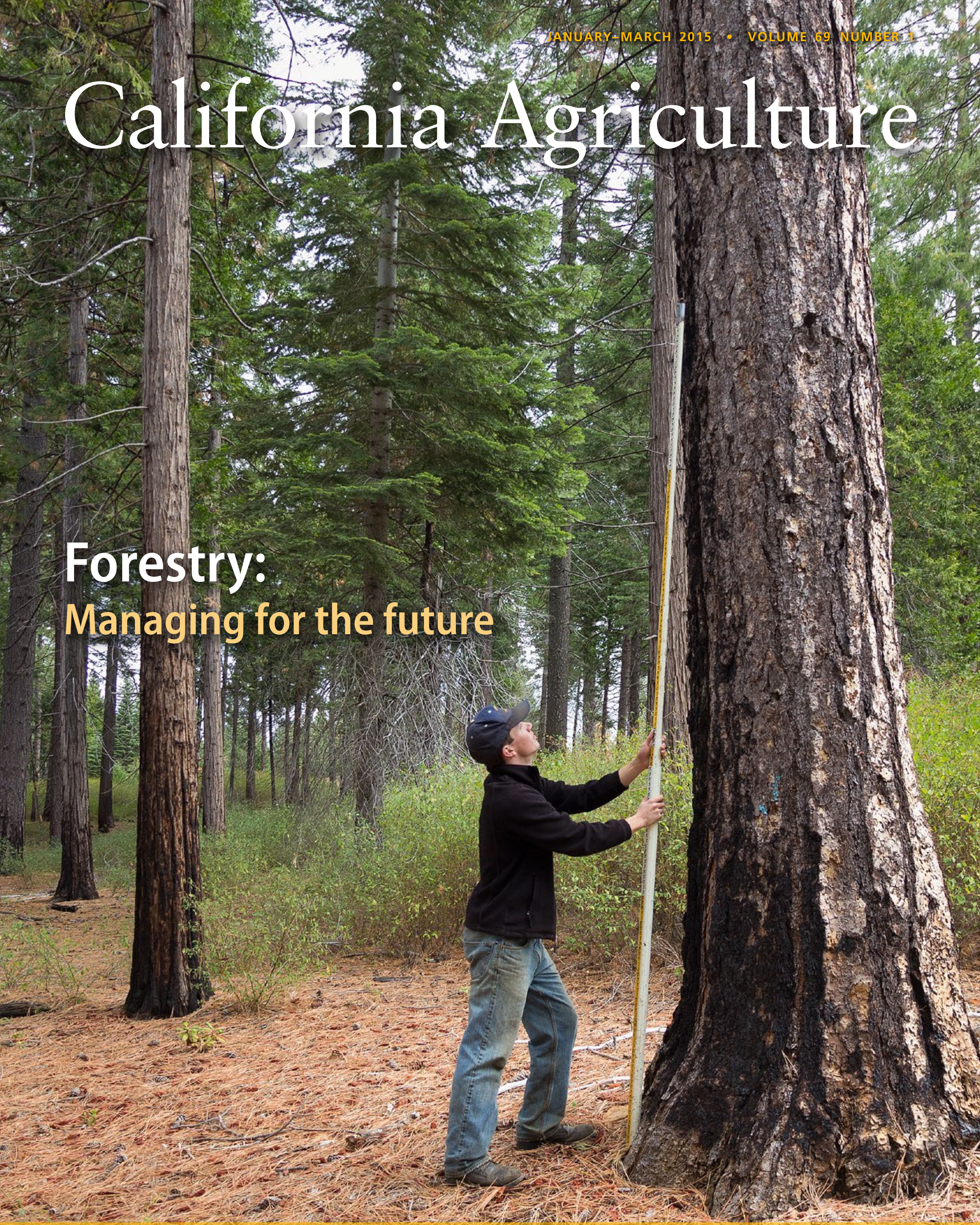
JANUARY–MARCH 2015 • VOLUME 69 NUMBER 1

California Agriculture

Forestry:
Managing for the future



University of California | Peer-reviewed Research and News in Agricultural, Natural and Human Resources

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University *of* California
Agriculture and Natural Resources

California Agriculture is a quarterly, peer-reviewed journal reporting research and reviews, published by the University of California Agriculture and Natural Resources (ANR). The first issue appeared in 1946, making *California Agriculture* one of the oldest, continuously published, land-grant university research journals in the country. There are about 10,000 print subscribers.

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TABLE OF CONTENTS

JANUARY–MARCH 2015 • VOLUME 69, NUMBER 1

COVER: Prescribed burning helps to reduce fuels on the forest floor, clear dense understory vegetation and increase diversity in forests. Controlled fires and mechanical treatments can greatly reduce the risk of catastrophic wildfire. In the cover photo, Darrik Carlson, a research assistant at UC Berkeley's Blodgett Forest Research Station in El Dorado County, measures the height of the charred bark on a 100-year-old mature tree after a prescribed burn. *Photo by Will Suckow*.

Editor's note:

California Agriculture gratefully acknowledges the faculty chair for this special issue: Richard Standiford, *California Agriculture* Associate Editor and UC Cooperative Extension Specialist in the Department of Environmental Science, Policy, and Management at UC Berkeley.


Evett Kilmartin

Forestry: Managing for the future

News departments

Editorial

4 UC Berkeley's forestry program celebrates 100 years
Gilless

Outlook

5 Californians must learn from the past and work together to meet the forest and fire challenges of the next century
Kocher

Research news

10 Forest thinning may increase water yield from the Sierra Nevada
Downing

12 Conifer encroachment study will inform efforts to preserve and restore North Coast oak woodlands
Downing

Research and review articles

14 **Mapping forests with Lidar provides flexible, accurate data with many uses**
Kelly and Di Tommaso
The powerful mapping capabilities of Lidar soon may be widely available to California forest managers as costs fall and the technology improves.

21 **Carbon calculator tracks the climate benefits of managed private forests**
Stewart and Sharma
Private forests that are harvested and regenerated yield approximately 30% more carbon sequestration benefits than if they are left to grow.

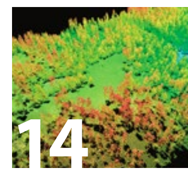
27 **Large-tree removal in a mixed-conifer forest halves productivity and increases white fir**
York
A long-term study in the Sierra Nevada confirms the negative consequences of preferentially removing large trees.

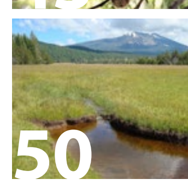
36 **Post-fire vegetation dynamics of a sagebrush steppe community change significantly over time**
Hanna and Fulgham
Nearly 30 years after a burn at two sites in northeastern California, sagebrush had recovered fully and invasive grasses had diminished.

43 **UC plays a crucial facilitating role in the Sierra Nevada Adaptive Management Project**
Sulak et al.
All sides of the Sierra forest management debate have learned from SNAMP. Can stakeholders help ensure research results are part of future management?

50 **Cooperative, cross-boundary management facilitates large-scale ecosystem restoration efforts**
Kelly and Kusel
A cooperative meadow restoration plan that successfully engaged a diverse group of stakeholders is a model for future projects.

57 **UC Cooperative Extension works with fire safe councils to reduce wildfires**
Nader and De Lasaux
The collaborative partnership has improved fire safety in fire-prone Plumas, Butte and Yuba county communities and stopped major wildfires.





UC Berkeley's forestry program celebrates 100 years

J. Keith Gilless

Dean, College of Natural Resources, UC Berkeley

In 2014, UC Berkeley celebrated the centennial of its forestry major. As with many other events in the university's history, the creation of the forestry program began with a push from student activists. In 1912, a group of agriculture undergraduates started a forestry club that has endured to the present. They pressed UC administrators and state legislators to establish a major in the subject, and in 1914 the Berkeley campus welcomed the first cohort of students to its new forestry program. Since then, the forestry issues addressed by UC teaching, research and extension programs have changed, but the tradition of serving society and the environment has continued unabated.

This issue of *California Agriculture* provides an opportunity to reflect on the past 100 years of forestry in California and the important partnership between our campus teaching program and the statewide UC Agriculture and Natural Resources (UC ANR) research and extension programs. All of the forestry faculty in UC Berkeley's College of Natural Resources have appointments in either the Agricultural Experiment Station or UC Cooperative Extension (UCCE). They often work closely with the statewide network of UCCE forestry and natural resource advisors based in county offices and the UC ANR research and extension centers.

With UC forestry experts addressing issues such as carbon sequestration, endangered species, catastrophic wildfire, invasive species and managing forests to enhance water yield, we are confident that our partnerships with the people of this state will remain relevant long into the future.

The articles in this issue show the range of research being conducted by the extended UC forestry community. Two articles highlight work from our educational partners in the California State University system. As we embark on the next century of forestry education in California, it has never been more important that UC Berkeley, Humboldt State and Cal Poly San Luis Obispo — which host the state's three accredited forestry educational programs — work together to educate a new generation of foresters. They will need a solid foundation to meet the high standards of California's licensing requirements and work successfully under the close public scrutiny of forest management demanded by the California Forest Practice Act.

Two UCCE advisors, Michael De Lasaux in Plumas and Sierra counties and Glenn Nader in Sutter, Yuba and Butte counties, authored an article about exciting grassroots extension partnerships with California's fire safe councils. The article on the Sierra Nevada Adaptive Management Program (SNAMP) by UC Berkeley Professor Lynn Huntsinger, UCCE Central Sierra Forestry Advisor Susan Kocher and UC Berkeley researcher Adriana Sulak illustrates UC ANR's effectiveness in bringing cutting-edge science to key forestry issues — fire management, wildlife habitat and water quality — faced by people across the state.

The Center for Forestry (ucanr.edu/sites/cff) coordinates much of the forestry research and extension work at UC Berkeley and also manages four forest properties. The article by the center's property manager, UC Berkeley Professor Robert York, describes a project in the crown jewel of California's research forests, Blodgett Forest Research Station in El Dorado County. Blodgett and our other properties are essential for outreach activities, helping to ensure that research is adapted and understood by the wide variety of stakeholders in California's forestland. We are excited for the future of our research forests, and have recently finalized plans to assume title to lands previously managed by Pacific Gas and Electric Co. that will bring our research forest footprint to 10,000 acres.

On September 19, 2014, more than 350 of our alumni, faculty, staff and friends gathered at the UC Berkeley Faculty Club to celebrate 100 years of forestry in California and recognize a century of accomplishments. Now we look forward, embracing the challenges of ensuring sustained uses of California's 40 million acres of forests and woodlands. With UC forestry experts addressing issues such as carbon sequestration, endangered species, catastrophic wildfire, invasive species and managing forests to enhance water yield, we are confident that our partnerships with the people of this state will remain relevant long into the future. CA

Will Suckow

Californians must learn from the past

and work together to meet the forest and fire challenges of the next century

Susan Kocher, Forestry/Natural Resources Advisor, UC Cooperative Extension Central Sierra

In 1920, forester Charles Ogle issued a warning about the emerging consensus that all wildfires in forests should be suppressed. "Under natural fire conditions," Ogle wrote in the July 1920 issue of *The Timberman*, "a proper amount of thinning was effected and the remaining trees were thereby given a better chance to mature." He predicted that trying to extinguish all wildfires would crowd the woods with small trees and leave forests prone to major fires and disease and warned that "a complete destruction of our standing timber of today and the elimination of possible second growth of practical value may be the result" (Ogle 1920).

Ogle and other prescribed-fire advocates lost the argument. Today their concerns seem prescient. After a century of fire suppression, California forests are denser and have fewer large trees. Severe fires are increasing in frequency and size throughout the Sierra Nevada. And regeneration is not a given for severely burned forests where seed trees have been killed across large areas.

UC U.S. Forest Service

The Rim Fire began in the Stanislaus National Forest on Aug. 17, 2013 and burned 257,314 acres. More than 100,000 acres burned at high severity, meaning nearly all trees were killed.

The fire-suppression stalemate

How have we gotten to this moment of crisis? Though land managers have understood for more than 40 years that fire has an important role in a functioning forest ecosystem, the use of fire to manage forests has remained limited. Fire suppression has led to dramatic increases in forest fuels, and letting wildfires burn now for ecological benefits and hazard reduction is considered too risky in most forests and weather conditions. Thinning forests of small trees and brush can reduce the severity of fires that burn there; however, paying for the work required to get those materials out of the forest is increasingly difficult as the number of mills and biomass-burning facilities has waned in the last decade. Additionally, biological, legal, operational and administrative constraints significantly limit where thinning can be carried out in the 10 national forests in the Sierra Nevada (North et al. 2015).

Decades of successful fire suppression lulled regulators of residential and commercial development into permitting new construction without regard to fire risk. These developments now reduce our ability to use fire to lessen future fire hazard. Attempts to get out of this predicament are made more challenging by political polarization over public land management, the uncertainties of a warming climate and concerns about the impacts of forest thinning on wildlife and the public health effects of smoke from prescribed fires.

Moving toward a healthier role for fire in California forests will be difficult. One area where there is opportunity, however, is in post-fire landscapes. Because today's wildfires tend to be so large and destructive, post-fire areas provide a large landscape on which to try to design a forest that will incorporate wildfire concerns from the beginning. Reforestation can be developed to incorporate fire and warming climate concerns. Restoration sites can also serve as an ongoing laboratory for experimentation, so that forest managers

A stand of ponderosa pine and sugar pine near Placerville in 1938. Fire scars on the large older trees show that frequent low severity fire (where most trees survive) was frequent in the area. Many new fir seedlings (which are shade tolerant) are establishing in the understory as a result of decades of fire suppression.

can continue to learn from experience and adapt to change. Hopefully this next generation of trees can provide many of the values that Californians expect from their forests.

The "light burning" controversy

Total fire suppression as a policy developed from several national concerns a century ago. Forest managers of the time were deeply affected by the Big Blowup of 1910 in Montana and Idaho, which burned more than 3 million acres, killed 85 people and destroyed several small towns. In addition, those fires consumed an estimated 7.5 billion board feet of timber. Foresters across the country had long been concerned about the possibility of timber famines, and so after those fires U.S. Forest Service Chief Henry Graves set the future policy: all-out fire prevention was the best way to protect America's forests and so the nation's economy.

Yet, 100 years ago, there were advocates for "light burning" in California. Native Americans and early settlers used light burning — or frequent prescribed fire, as it would be called today — to thin out forests and reduce fuels, and thereby to protect large trees from bigger fires in the future. Prescribed fire also was used to promote forage and edible plants, especially oaks, whose acorns were a staple food for California Indians.

For decades after its adoption as national policy, aggressive fire suppression mostly had the desired effect. The Sierra Nevada is a productive nursery for trees in its middle elevations and standing biomass in forests there, and throughout California, increased in the absence of fire. Indeed, reserve areas at UC Berkeley's Blodgett Forest Research Station show that undisturbed and unburned forests have continued to accumulate wood since the last harvest 100 years ago. Young trees "saved" by fire suppression efforts grew large and were harvested to support the state's rapid growth.

From the 1930s to the 2000s the number of large trees in the Sierra Nevada decreased by half while the density of small trees doubled.

The unanticipated effects of fire suppression

What was not obvious to foresters 100 years ago was that it would eventually become impossible to contain and suppress wildfires in increasingly dense and warming forests. The buildup of forest fuels in areas of the Sierra Nevada that have not burned in a century is staggering. A recent statewide analysis of historical data found that from the 1930s to the 2000s the number of large trees in the Sierra Nevada decreased by half while the density of small trees doubled (McIntyre et al. 2015). Another recent study, of a site in the central Sierra Nevada, found nine times as many dead standing trees and three times as many dead logs on the ground than were recorded in 1929. In addition, the dead wood in the forest today is smaller and thus more flammable (Knapp 2015).

Trees burned by the Rim Fire in the Stanislaus National Forest. In this patch, almost all old large trees that would have survived frequent low severity fires due to thick bark and architecture (branches held very high up on the stem) have been killed. This leaves little seed source for the next generation of seedlings.

Before fire suppression, roughly 5% to 10% of acres burned in wildfires burned at the "high severity" level, intense enough to kill most mature trees. By contrast, 40% or more of the acreage in recent major fires — such as the 2013 Rim Fire in the Yosemite National Park area and the 2014 King Fire in El Dorado County — has burned that severely.

Fire suppression also affects forest species composition. In the Sierra Nevada, it favors trees that can survive in low light conditions on the forest floor, such as white fir and incense cedar, over those that thrive in open sunny conditions such as ponderosa and sugar pines. Unfortunately, the greatly increased numbers of firs are less likely than pines to survive fire and drought. As a result, many Sierra Nevada forests are much less resilient to water stress and fires, which are exacerbated by a warmer climate.

Foresters 100 years ago also could not have anticipated the cultural and policy shifts that resulted in not harvesting all the trees they so carefully protected from fires. Gone is the social consensus that harvesting timber from forests is a necessary building block of the economy. For decades, public opinion has generally favored policies that support the non-timber values that forests provide, such as recreation, wildlife habitat, spiritual refuges, scenic beauty and the preservation of natural, wild spaces.

The next 100 years

Emerging issues are continuing to change what California wants from its forests. The role of forests in California's water supply system, for instance, is gaining increasing attention. The Sierra Nevada receives around 30% of the state's annual precipitation as rain or snow but provides almost 60% of the state's water needs. Sierra Nevada forests historically have stored about 15 million acre-feet of water as snowpack each winter. Fire suppression has impaired these water storage and supply functions by increasing the amount of water used by vegetation in overcrowded forests, thus decreasing the amount of water that flows from them. Severe fires also leave the forest floor bare and vulnerable to soil erosion, which often results in degraded water quality. In this season of drought, Californians need resilient forests to provide a reliable water supply.

Tour of Rim fire area in the Stanislaus National Forest, March 2014. Participants are looking at high severity fire effects where all trees were killed.

Climate change is also rapidly changing how fires burn. Average temperatures in California are projected to exceed pre-industrial levels by 3°F to 10°F by the end of the century, shrinking the annual Sierra Nevada snowpack as much as 90%. Warmer temperatures and a smaller snowpack mean forests will become dry sooner, fire seasons will last longer and accidental ignitions during (the more numerous) dry, windy days will be more likely to cause severe wildfires.

Restoration: An experimental approach

To address the current crisis, forest managers, researchers, policymakers and the public must work together to increase the resilience of our forests to climate change and wildfire. We must do this even though we, just like the foresters from the turn of the last century, cannot predict the social and ecological conditions in the next century with any certainty.

On public land, increasing the pace and scale of forest fuel reduction treatments is critical, as is more use of prescribed and managed fire.

Susie Kocher

Volunteers for the League to Save Lake Tahoe install erosion control measures following the 2007 Angora fire near South Lake Tahoe. The fire burned 3,100 acres, destroying 250 residences.

On private land, changes in the California Forest Practices Act, which sets tree harvesting and replanting requirements, may be needed to allow the planting of seedlings from areas more suited to the coming climate and to reduce the density of plantations that lead them to be at high risk for fire. Reducing fuels — by thinning, mastication or prescribed fire — is typically expensive, so owners of small forest tracts, which typically do not produce income, need technical and financial assistance in identifying and addressing their climate risks through forest fuels reduction, thinning, planting and disposing of dying trees.

The forests of the Sierra Nevada now contain severely burned patches totaling hundreds of thousands of acres. In many of these areas, where all seed-bearing trees have been killed, trees may not regenerate naturally. Replanting of post-fire areas traditionally has been dense, with over 400 seedlings planted per acre and thinning conducted within the first 10 years. This high-density planting helps trees outcompete shrubs. However, public forest managers often no longer have the capacity to conduct thinning or weed control, leaving untreated, fire-prone stands that are a risk to neighboring forests. Some post-fire areas, such as those on steep, south-facing slopes, may be so fire-prone that reforestation efforts would be wasted; indeed, they probably would not support trees at all (only shrubs) if not for long-term fire suppression.

Moving forward, post-fire restoration should incorporate four key approaches: planning for wildfire and prescribed fire, promoting a diverse forest landscape, anticipating climate change and investing in ongoing experimentation and monitoring.

Plan for wildfire and prescribed fire. Restoration plans should incorporate a fire hazard analysis to help identify restoration priorities and locations. For example, areas where topography and prevailing winds would lead wildfires into communities should be prioritized for removal of dead trees to reduce fuels and the risk from future fires. New plantations should be minimized in areas with the highest fire hazard, such as inner canyon walls with steep slopes; these areas may be better suited to remain in shrub cover to benefit wildlife species that prefer an open, shrub-dominated habitat. Recently burned areas most conducive to prescribed fire should be identified and a plan made for reburning them as fuels accumulate,

The forests of the Sierra Nevada now contain severely burned patches totaling hundreds of thousands of acres.

A volunteer for the League to Save Lake Tahoe plants a seedling after the Angora fire of 2007. A group of 350 volunteers worked to restore California Tahoe Conservancy land where all trees were killed by the fire.

Susie Kocher

probably within 10 to 15 years in the lower and middle elevations of the Sierra Nevada. Where possible, new plantations should be designed to allow prescribed fire as a management practice, by spacing trees appropriately and incorporating fuel breaks.

Promote diverse forest landscapes. Post-fire restoration plans should also incorporate heterogeneity on the landscape. Recent controversies over post-fire salvage logging after large fires have focused on how many standing dead trees, or snags, to retain for wildlife habitat. Although some advocate for leaving all dead trees alone, very large fires may actually leave more areas of shrubs and standing dead trees than desirable. Instead these landscapes are now lacking in areas of young and old living trees. In these cases, management actions could focus on dead tree removal (to remove future fuels), replanting where future fire risk is lowest and fuel reduction treatments in any stands of old trees within the burns or in nearby forests. The result of this combination of actions would be a mosaic of areas with a variety of ecosystem characteristics, and wildlife habitats, and a reduction in future fire risk.

Anticipate climate change. Restoration projects should start with a climate vulnerability assessment to identify areas where warming will cause the most effects. In areas where the most change is projected, such as lower-elevation south-facing slopes, experiments should be conducted to evaluate planting arrangements, species and seed source and management strategies. Areas that have experienced low-severity fire can be designated as climate refugia, providing bases from which current tree species can migrate to new locations as the climate changes.

Invest in experimentation and monitoring. Learning from post-fire restoration requires that managers explicitly consider these actions as experiments. The history of fire suppression illustrates the need to consider any management as an endeavor that must be reevaluated as social and ecological conditions change. Forest managers and researchers should work together to develop experimental approaches, document successes and failures and share learning around restoration outcomes. The approaches and questions addressed must be shared with stakeholders, including communities in fire-prone areas, so that public opinion can influence and evolve with our understanding of effective post-fire restoration techniques.

The way forward

It is often said that our government and military are busy refighting the last war instead of fighting the current one, that our definitions of the problems we face and our strategies for combatting them are no longer relevant under current conditions. We have developed a sophisticated fighting force to suppress wildfire at all costs — even though we can no longer succeed at suppression, and suppression often makes the impacts of future fires more severe. Fire and forest management strategies developed 100 years ago may have made sense at the time, but after 50 years it was obvious, at least to some, that the fire exclusion strategy was at best ineffective and at worst a tragedy in the making (the National Park Service abandoned total fire suppression at about that time). Now, immediate changes in policy are needed from the rest of our state and federal forest and fire agencies.

Moving forward to change the failed policies of the past will be difficult, especially as the prolonged drought of the last few years has made forests more flammable. Yet, there is an opportunity in both burned and unburned areas to test a new approach to forest management. Burned areas in the Sierra Nevada provide forest managers with a laboratory for experimentation and a chance to create forests that can better adapt to the fire and climate conditions of this century and the next. CA


Susie Kocher

Tahoe Conservancy and League staff carry Jeffrey pine and incense cedar seedlings for planting about 30 acres in the Angora burn area.

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Forest thinning may increase water yield from the Sierra Nevada

Discussions of California's limited water supplies often leave out the biggest water users of all — forests.

But an average of roughly 50% of the precipitation that falls in the Sierra Nevada never makes it to the state's rivers, groundwater basins, reservoirs and aqueducts. Instead, it sustains trees and other vegetation, or evaporates.

A team of UC researchers is investigating how thinning forests could increase the water yield of the Sierra Nevada, which supplies about 60% of the surface water used by California's cities and farms.

The Sierra Nevada Watershed Ecosystem Enhancement Project (SWEEP) builds on prior research that indicates that forest thinning — removing a fraction of trees and other vegetation — can improve the health of remaining trees and reduce the risk of severe wildfire (Bales et al. 2011; Collins et al. 2014).

About 60% of California's developed water supply originates in the Sierra Nevada.

The research team aims to quantify how investments in forest management translate to increases in the amount of runoff from a given watershed. While research from a variety of sites around the world shows that thinning can increase water yield, the magnitude of that effect varies widely depending on climate, elevation and other variables, and it isn't well studied in the Sierra Nevada.

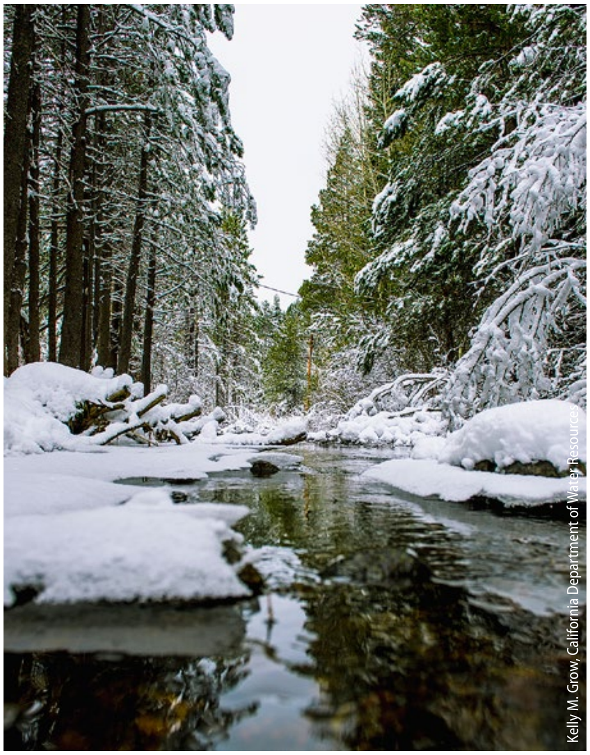
Better data on the benefits of vegetation management — for water availability as well as forest health, fire vulnerability, wildlife habitat and other ecosystem services — could form the basis for deals creating new sources of funding for forest management. Owners of hydroelectric dams, for instance, might chip in for watershed management if it was clearly established that a healthier forest would mean more water flowing through turbines downstream. But such transactions would need to be based on solid research.

"You need good data if you're going to ask people to pay for it," said Roger Bales, a hydrologist and professor of engineering at UC Merced and a lead SWEEP researcher.

Marketing the ecosystem benefits of forest thinning could help address a key problem in forest management: While there is wide agreement that tree density is higher than desirable on much California forestland, funding is scarce for thinning, which typically costs $300 to $500 per acre. Preliminary estimates suggest that reducing forest cover by 40% could be expected to increase water yield about 9%.

Bill Stewart, a UC Cooperative Extension specialist who is studying the economic aspects of SWEEP,

Elena Zhukova



Recent snowfall near the headwaters of the South Fork of the American River in the Eldorado National Forest. Climate change is expected to decrease average winter snowpack in the Sierra Nevada 25% by 2050.

said that the additional water generated by a thinning project is, on its own, not likely to be worth enough to cover costs. In addition, such water benefits likely would be tough to monetize and sell, because they would fluctuate a great deal from year to year. In very dry years, for instance, a thinned forest generally won't yield appreciably more water than a dense one.

But, Stewart said, it does appear that combining revenue from multiple sources — money from sawlogs (harvested trees that can be milled into lumber), biomass power generation, contributions from groups with a stake in fire risk reduction, payments from hydroelectric generators and so on — could cover the cost of thinning, even without taking into account possible payments from downstream water users.

"The water is the icing on the cake," he said.

Restoring vegetation densities to pre-fire-suppression levels through thinning could increase California's usable water supply meaningfully, according to calculations by Bales. He estimates that thinning 500,000 to 600,000 acres of forest would increase average water yield by 100,000 acre-feet.

However, Bales notes, recent research indicates that some of this potential water gain from thinning would be lost to higher rates of evapotranspiration as the climate warms. A 2014 study co-authored by Bales shows how a warming climate will drive increased vegetation and water consumption at high elevations as plant communities expand uphill and warmer temperatures extend the growing season (Goulden and Bales 2014).

Thinning 500,000 to 600,000 acres of forest could increase average water yield by 100,000 acre-feet.

The changing climate also is expected to decrease average winter snowpack 25% by 2050, a major reduction to a natural storage system that has historically held an average of 15 million acre-feet of water that is gradually released during spring, summer and fall.

These worrisome trends are driving increased concern about water yield from the Sierra Nevada. The scope of thinning contemplated by land managers and the SWEEP researchers could ameliorate these climate-driven reductions to some degree.

SWEEP, which launched in 2011, is still in its early stages. Supported by a UC Agriculture and Natural Resources grant, the team is currently working on detailed planning and funding for what is expected to be a decade-long field research effort. CA

— Jim Downing

Ponderosa pine stand near Blodgett Forest Research Station in El Dorado County. Less-dense forests tend to yield more water.

Further reading:

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Conifer encroachment study

will inform efforts to preserve and restore North Coast oak woodlands

On California's North Coast, landowners have noticed for decades the steady expansion of conifer stands into grassy oak woodlands.

"It's one of those things that creeps up on you — not a radical change, but just a clearly shifting trend," said Dina Moore, a rancher in the Van Duzen River watershed near Eureka.

Conifer encroachment on the North Coast matters because it shrinks the already limited acreage of oak woodlands, one of the state's iconic landscapes. Oak woodlands are valuable for several reasons, including grazing, hunting and habitat for oak-associated wildlife communities. Several counties are preparing oak woodland conservation plans, and the U.S. Fish and Wildlife Service and the Natural Resources Conservation Service have been providing grants to landowners to pay for tree removal to counter the trend.

A 1987 study estimated that 30% of the white oak woodlands in one region of Redwood National Park had been lost to encroachment by Douglas fir since 1850.

But these efforts have been hampered by both a poor understanding of the extent of conifer encroachment in the region and a lack of research on the best ways to address it. A 1987 study estimated that 30% of the white oak woodlands in one region of Redwood National Park had been lost to encroachment by Douglas fir since 1850, but there has been limited research since on the encroachment issue.

Fire suppression helps to create conditions that allow conifers to sprout and mature among oaks, as in this woodland in Redwood National Park.

Encroaching conifers obscure a stand of oak in Redwood National Park.

Better information is coming this fall, with the publication of results from a three-year investigation funded by UC Agriculture and Natural Resources (UC ANR) and led by UC Cooperative Extension (UCCE) researchers.

The project, "Tools for a changing landscape: Understanding disturbance and vegetation dynamics in Northern California oak woodlands," is using aerial photography and satellite data to generate the first comprehensive map of oak woodland areas in Humboldt and Mendocino counties. Researchers will compare current conditions with historic photos and other data, along with field measurements of tree ages and other characteristics, to evaluate the extent and impact of Douglas fir encroachment.

The project has established field sites in multiple locations to study climate, moisture and other conditions that may influence encroachment patterns. The information gathered will also help researchers to predict how climate change may affect the encroachment process.

The California black oak and Oregon white oak woodlands of the North Coast are fire-adapted, meaning that they depend on frequent, low to moderate intensity fires to prevent establishment of invading fire-sensitive vegetation — including conifer species such as Douglas fir — and to help provide the conditions necessary for new oaks to sprout and develop to maturity.

Decades of fire suppression have allowed Douglas fir and other conifers to become established in oak woodland areas, many of which contain oaks that are hundreds of years old. The study has found that the encroachment trend accelerated in several of the research sites starting in the 1960s, though it's not clear why. The Douglas fir invasion is a part of the overall trend of forest densification that has been observed throughout the western United States in the absence of natural disturbance regimes like fire.

Reversing the encroachment process is difficult, in part because conifer stands create conditions that make it more difficult to use fire as a management tool. For instance, Douglas fir trees become fire resistant as they grow in size, reducing the effectiveness of prescribed fire and adding another layer of complexity to already costly oak woodland restoration strategies. As a result, manual removal of some trees may be necessary before prescribed fire can be used to help restore and maintain oak woodland conditions.

"Once the conifers get a foothold, the oaks lose," said Yana Valachovic, a UCCE forest advisor, director for UCCE Humboldt and Del Norte counties and one of the principal investigators on the project. "The oaks are not regenerating, and the amount of oak woodland area is shrinking as a result of the encroachment."

Larger conifers can be removed by manual thinning, but that work tends to be very labor intensive and costly, particularly in remote areas, said Moore, the landowner. In addition, the trees that need to be removed generally have little or no market value as timber, and many areas have no access to biomass energy markets. "Landowners would like to have an option for commercial utilization of the conifers, to not have to rely on government funded cost-share programs alone," said Valachovic.

Guidance on management changes that landowners could take to prevent encroachment in the first place would help. One of the goals of the conifer encroachment project, Valachovic said, is to develop a decision support system to help landowners determine what management approaches are likely to be most effective on their property.

Policy constraints and unfavorable economics make it difficult to remove established conifer trees from stands of oak.

California's forest management policies make the conifer encroachment problem even knottier.

Under the California Forest Practice Rules, established by the 1973 Forest Practices Act, landowners are required to replant conifer stands after harvesting trees. In conifer forests managed for timber, the rule makes sense. But it doesn't currently include an exception for cases where a landowner is trying to restore an oak woodland by removing conifers.

Valachovic and her UC ANR colleagues have gone before the California Board of Forestry to testify about the need for a rule change and also authored a policy brief arguing for a rule change. There is a precedent for amending the Forest Practice Rules to enable restoration; in 2012, the state Board of Forestry adopted an amendment allowing conifers to be removed from aspen stands and meadows for restoration purposes. Later this year, the state Legislature will consider a proposal to amend the rules in a similar way for oak woodlands. CA

— *Jim Downing*

Prescribed fire can help to stop the spread of Douglas fir trees into open oak woodlands, as in this burn in Redwood National Park. But Douglas fir become more fire resistant as they mature.

Mapping forests with Lidar provides flexible, accurate data with many uses

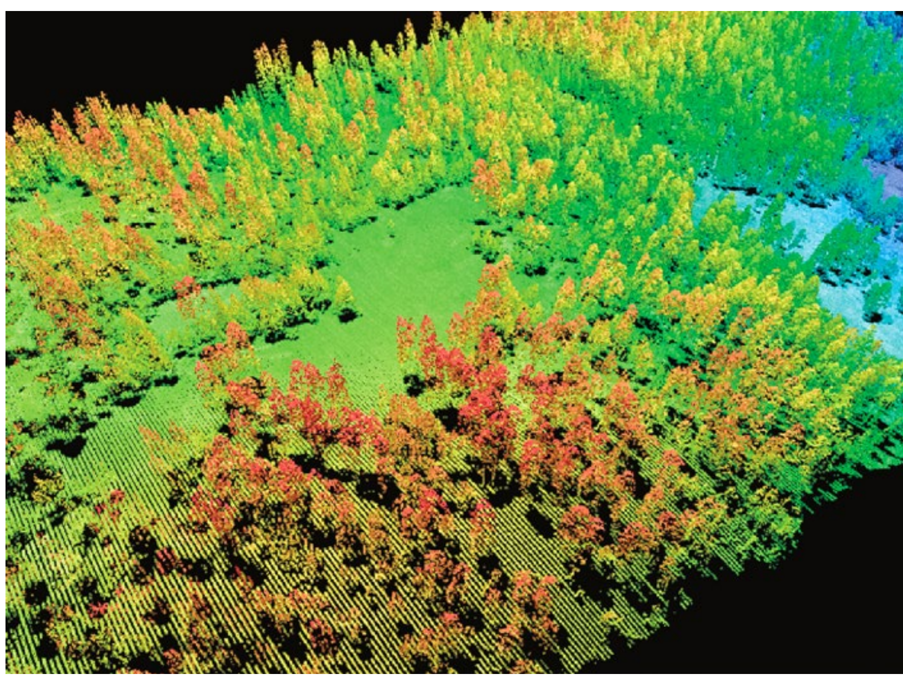
by Maggi Kelly *and* Stefania Di Tommaso

The use of remote sensing for forest inventory, fire management and wildlife habitat conservation planning has a decades-long and productive history in California. In the 1980s, mappers transitioned from aerial photography to digital remote sensing, in particular Landsat satellite imagery, which still plays a significant role in forest mapping, but today mappers increasingly rely on Lidar analysis. In California, where forests are complex and difficult to accurately map, numerous remote sensing scientists have pioneered development of methodologies for forest mapping with Lidar. Lidar has been used successfully here in a number of ways: to capture forest structure, to map individual trees in forests and critical wildlife habitat characteristics, to predict forest volume and biomass, to develop inputs for forest fire behavior modeling, and to map forest topography and infrastructure. Lidar can be costly to acquire and difficult to analyze, but as costs decline and new data processing methods are developed, it is likely that forest managers who need detailed information on forest structure across large spatial scales will incorporate Lidar data into their mapping toolkits.

Mapping has always been critical for forest inventory, fire management planning and conservation planning. In California, these tasks are particularly challenging, as our forests exhibit tremendous variability in composition, volume, quality and topography. Also, California is a fire-prone state, and our forests are used by a large number of important wildlife species. Perhaps it is due to this natural complexity that researchers have focused on California forests to pioneer solutions to many of the difficult problems in remote sensing.

Prior to about 1980, forest inventory and habitat mapping largely relied on manual interpretation of vertical-view aerial photography (Arvola 1978; Colwell 1964, 1965), but the launch of Landsat-1 and Landsat-2 satellites from Vandenberg Air Force Base in California in 1972 and 1975 (Lauer et al. 1997) permanently changed the way forests were mapped. Digital mapping of canopy, phenology and condition over large scales and through time became possible. The early excitement about Earth observation satellites in terms of forestry applications (Colwell 1973; Fritz 1996; Gregory 1971; Strahler 1981) foreshadowed three decades of intense and increasing use of Landsat imagery by land managers, regulatory agencies, scientists and nongovernmental organizations in California to map forest vegetation and mortality, explore forest change detection, map fire severity and map wildlife habitat. Landsat was the workhorse of forest remote sensing before the turn of the century, but advances in sensor design, data processing and information synthesis then revolutionized the field (Wulder et al. 2003).

The MODIS satellite was launched in 1999, making it possible to study forests at a global scale at a temporal resolution not available before (Lefsky 2010; Running et al. 2004). At the local scale, high-resolution stereo-matched optical imagery was used to map forest structure (Gong et al. 1999; Gong et al. 2000; Sheng et al. 2001; Sheng et al. 2003). Landsat-8, launched in 2013, and high-resolution optical sensors such as Worldview-2 and -3 continue to be useful for forestry. But more recently, Lidar (light detection and ranging) has become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Collections of Lidar points show trees in the Sierra National Forest, where much of the research on remote sensing has occurred.

Online: http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v069n01p14&fulltext=yes
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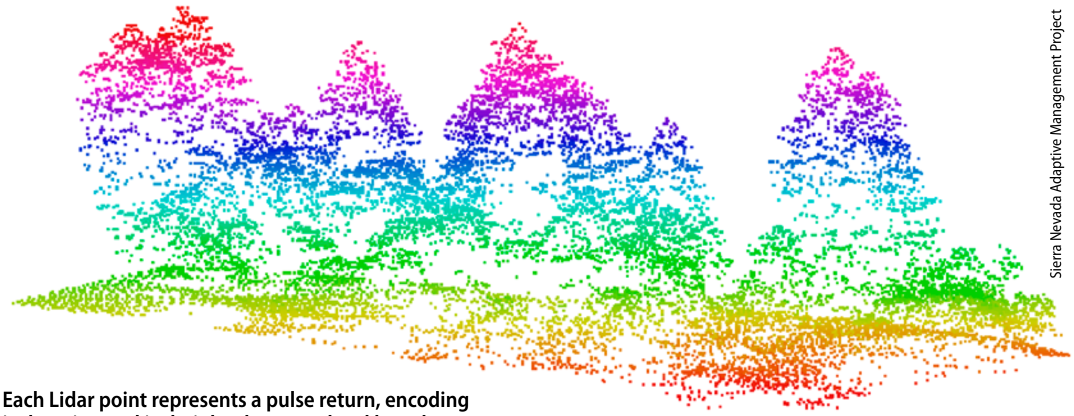
an operational, accurate and reliable tool for detailed mapping of forests.

Lidar technology

Lidar is an active remote sensing technology used to measure distances with high accuracy. This technology provides horizontal and vertical information at high spatial resolution and vertical accuracies, offering opportunities for enhanced forest monitoring, management and planning (Dubayah and Drake 2000; Lim et al. 2003; Reutebuch et al. 2005). Lidar systems for forestry are classified according to the platforms they are mounted on (airborne, spaceborne or ground based), on the way returned signals are recorded (discrete return or full waveform) and on the footprint size (i.e., the horizontal illuminated area) — a small footprint covers ~ 3 feet (~ 1 meter) or less, a large footprint covers tens of meters. The most common Lidar systems used today are small-footprint, discrete return laser scanners mounted on aircraft (although this is rapidly changing). The laser scanner measures distances to a target by emitting pulses at rapid frequency, up to 150 kilohertz (kHz), and recording the time it takes for each pulse to complete the distance from the scanner to the object and back to the scanner.

Airborne laser scanning systems have four major components: a laser scanning unit, a global positioning system (GPS), an inertial measurement unit (IMU) and a computer to store data. The first three components yield the precise time and the position of the laser unit when each pulse is emitted. With discrete return Lidar systems, multiple returns (up to five) from a single outgoing pulse can be recorded to produce vertical information about vegetation above the ground as well as at the ground surface. The result is a dense, three-dimensional point cloud representing the vegetation and ground surface topography of the surveyed landscape.

Full waveform Lidar systems record the entire waveform of the reflected laser pulse, not only the peaks as produced by the discrete multiple return Lidar systems. The reflected signal of each emitted pulse is sampled in fixed time intervals, typically 1 nanosecond (ns), equal to a sampling distance of 6 inches (15 centimeters) at a typical flying height. This provides a quasi-continuous, extremely high-resolution profile of the vegetation



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Each Lidar point represents a pulse return, encoding its location and its height above sea level by color. The technology can delineate individual trees in oak savanna and mixed-conifer stands.

canopy structure, making it suitable for wildlife habitat mapping and the analysis of vegetation density, vertical structure and fuels analysis. The downside of the waveform technology is the huge amount of data that needs to be stored and processed; full waveform data sets drastically increase processing time and complexity compared with discrete data, and there are fewer commercial software packages designed to process full waveform data over large project areas.

Lidar use in California forests

Since about 2000, Lidar has been increasingly used by researchers to map California forests. Lidar has been used successfully to capture forest structure, to map individual trees in forests and critical wildlife habitat characteristics, to predict forest volume and biomass, to develop inputs for forest fire behavior modeling and to map forest topography and infrastructure. We reviewed 24 peer-reviewed papers covering this research (table 1). Some papers focus on oak woodlands and savannas (Chen et al. 2006; Chen et al. 2007) and coast redwood (Chen 2010; Gonzalez et al. 2010), but the majority focus on the conifer and mixed-conifer forests in the Sierra Nevada. The Sierra National Forest is the forest that has been most often remotely sensed in California; nine of the papers we reviewed focused on this forest; it has been mapped with large- and small-footprint, discrete and waveform Lidar, as well as with Landsat, Quickbird and other sensors.

Forest structure. Understanding the structure of forests — the tree density, volume and height characteristics — is critical for management, fire prediction and wildlife assessment. Optical remote sensors such as Landsat do not provide detailed depictions of forest structure. Several Lidar studies of California forests focus on using Lidar to develop forest structure parameters, such as tree height and trees per acre. There are typically two methods to perform large-scale forest inventory with small-footprint Lidar data: (1) at the scale of individual trees and (2) at the stand or plot scale.

The ability to delineate individual trees from a Lidar point cloud has been proven for heterogeneous and complex forests such as oak savanna (Chen et al. 2006; Chen et al. 2007) and mixed-conifer stands (Li et al. 2012). Delineating the individual trees is done by segmenting the Lidar-derived canopy height model — the raster image interpolated from Lidar points depicting the top of the vegetation canopy (e.g., Chen et al. 2006) — by delineating the trees directly from the point cloud (Li et al. 2012) or by a combination of these methods (Jakubowski, Li et al. 2013). After accurate segmentation, relationships can be derived between Lidar- and field-measured structural attributes such as tree height, crown diameter and canopy base height, which are directly measured, and basal area, diameter at breast height, wood volume, biomass and species type, which are derived by correlations (Chen et al. 2006; Chen et al. 2007).

The development of plot- or stand-scale predictions of forest structure with Lidar requires regression between field data and Lidar metrics derived from the point cloud (e.g., height and height profiles and percentages) that reports overall goodness-of-fit measures (e.g., correlation coefficient R^2) and measures of uncertainty (e.g., root-mean-squared error, RMSE). Jakubowski, Guo, Collins et al. (2013) found that many forest canopy structure metrics resolved at the plot scale (e.g., canopy height, canopy base height, canopy cover, basal area) were estimated well with discrete Lidar data (R^2 = 0.87 for canopy height).

There is a trade-off between detail, coverage and cost with Lidar. The accurate identification and quantification of individual trees from discrete Lidar pulses typically require high-density data. Jakubowski, Guo and Kelly (2013) investigated the relationship between Lidar pulse density and the ability to predict commonly used forest metrics at the plot scale in Sierra Nevada mixed-conifer forests. Results show that the accuracy of predicted plot-scale metrics remains relatively high until about 0.1 pulse per square foot (1 pulse per square meter). However, higher-density (up to 1 pulse per square foot, or 10 pulses per square meter) data are necessary for metrics related to coverage (e.g., tree density, canopy base height and shrub cover) and for the delineation of individual trees.

Studies using large-footprint, full waveform data for forest inventory in the Sierra Nevada forests have demonstrated the ability of full waveform Lidar to retrieve accurate canopy fuel maps needed for fire behavior modeling (Peterson et al. 2005) and to provide an accurate estimate of leaf area index at multiple spatial scales (Tang et al. 2014). Zhao et al. (2013) compared the abilities of an airborne and a ground-based full waveform system to retrieve foliage profiles in the Sierra National Forest and showed the benefits of integrating terrestrial and airborne Lidar data for a detailed description of forest canopy structure.

Hyde et al. (2006) explored the potential of retrieving accurate canopy height from large-footprint satellite Lidar waveform data over forests in the Sierra National Forest. They focused on the synergic use of Lidar with other sensors, in particular Landsat ETM+, to increase canopy height prediction accuracy. Chen (2010) also used large-footprint satellite Lidar waveform data over forests but

Table 1. Key papers discussing Lidar for forest mapping in California

Reference	Lidar type	Location, forest type	Scale (e.g., hectare, stand, individual tree)	Topic
Hyde et al. 2005	Full waveform, large footprint	Sierra Nevada Forest, mixed conifer	Lidar footprint and stand	Wildlife habitat: spotted owls
Hyde et al. 2006	Full waveform, large footprint	Sierra Nevada Forest, mixed conifer	Lidar footprint and stand	Canopy height and biomass
Peterson et al. 2005	Full waveform, large footprint	Sierra National Forest, mixed conifer	Lidar footprint	CBD, CBH
Chen et al. 2006	Small footprint, discrete	Ameriflux site at Ione, oak savanna	Individual tree	Individual tree isolation
Chen et al. 2007	Small footprint, discrete	Ameriflux site at Ione, oak savanna	Individual tree	Basal area, stem volume
Chen 2010	Spaceborne: full waveform, large footprint; airborne: small footprint, discrete	Mendocino County, conifer; Santa Clara County, broadleaf woodland	Lidar footprint	Canopy height
Gonzalez et al. 2010	Small footprint, discrete	Mailliard Redwoods State Natural Reserve, coast redwood forest; Tahoe National Forest, mixed conifer	Stand	Forest carbon
Guo et al. 2010	Small footprint, discrete	Tahoe National Forest, mixed conifer	NA	DEM
White et al. 2010	Small footprint, discrete	Santa Cruz Mountains, coast redwood	NA	Forest road mapping
Garcia-Feced et al. 2011	Small footprint, discrete	Tahoe National Forest, mixed conifer	Individual tree	Wildlife habitat: spotted owls
Swatantran et al. 2011	Full waveform, large footprint	Sierra National Forest, mixed conifer	Stand	Biomass
Blanchard et al. 2011	Small footprint, discrete	Tahoe National Forest, mixed conifer	NA	Downed logs
Chen et al. 2012	Small footprint, discrete	Sagehen Creek Experimental Forest, mixed conifer	Stand	Biomass
Lu et al. 2012	Small footprint, discrete	Sagehen Creek Experimental Forest, mixed conifer	Stand	Biomass
Li et al. 2012	Small footprint, discrete	Sierra National Forest, mixed conifer	Individual tree	Individual tree segmentation
Zhao, Guo, Kelly 2012	Small footprint, discrete	Sierra National Forest, mixed conifer	Plot and individual tree	Biomass
Zhao, Sweitzer et al. 2012	Small footprint, discrete	Sierra National Forest, mixed conifer	Plot and individual tree	Wildlife habitat: Pacific fisher
Jakubowksi, Li et al. 2013	Small footprint, discrete	Tahoe National Forest, mixed conifer	Individual tree	Individual tree segmentation
Jakubowksi, Guo, Collins et al. 2013	Small footprint, discrete	Tahoe National Forest, mixed conifer	Stand	Surface fuel model and metrics
Jakubowksi, Guo, Kelly 2013	Small footprint, discrete	Tahoe National Forest, mixed conifer	Plot	Lidar pulse density vs. metrics accuracy
Zhao et al. 2013	Full waveform, large footprint	Sierra National Forest, conifer	Plot	Foliage profile
Kane, Lutz et al. 2013	Small footprint, discrete	Yosemite National Park, mixed conifer forest and red fir forest	90-meter (0.81-hectare) grid cell	Fire effects on forest spatial structure
Kane, North et al. 2013	Small footprint, discrete	Yosemite National Park, mixed conifer forest and red fir forest	30-meter grid cell	Fire severity effects on forest structure
Tang et al. 2014	Airborne and spaceborne: full waveform, large footprint	Sierra National Forest, mixed conifer	Plot	LAI

concentrated on coastal California forests in Mendocino County (dominated by coast redwood and Douglas fir) and Santa Clara County (coast live oak forest and blue oak woodland, with some mixed-evergreen forest). Chen studied the effect of footprint size on canopy height estimation and showed the need to reduce footprint size to 32 feet (10 meters) or less if meter-level accuracy is to be achieved.

Wildlife. Several studies of California forests have used Lidar to capture important habitat characteristics relevant to forest-dwelling wildlife, such as nesting or denning structures. Hyde et al. (2005) examined the ability of large-footprint Lidar to retrieve forest structural attributes (slope, elevation, aspect, canopy cover, crown shape and the spatial arrangement of canopy-forming trees) that are important for California spotted owl (*Strix occidentalis occidentalis*) in the Sierra National Forest. They found good agreement between field and Lidar measurements of height, cover and biomass at the footprint level and canopy height and biomass at the stand level. Garcia-Feced et al. (2011) performed a similar assessment with small-footprint discrete data in the Tahoe National Forest. They mapped the canopy cover and the number, density and pattern of all the large residual trees within 656 feet (200 meters) of four nest sites for spotted owls.

Resting and denning structures are considered to be the most important habitat elements required for maintenance of Pacific fisher (*Martes pennant*) populations, and literature has shown strong associations between fisher denning activity and its surrounding forested environment. Zhao, Sweitzer et al. (2012) compared trees used by fishers for denning with trees not used by fishers and found that denning structures were associated with high canopy cover, large trees and high levels of vertical structural diversity, and that the denning structures were located on steeper slopes, potentially associated with drainage areas with streams or access to water.

Fire. To mitigate the possibility of large areas of high-severity fire, managers use wildfire behavior modeling for planning fuel reduction treatments such as thinning and prescribed fire across public forests. Forest fire behavior models need a variety of spatial data layers to accurately predict forest fire behavior, including elevation, slope, aspect, canopy height,

Right, **UC Berkeley Ph.D. student Marek Jakubowski uses a laser range finder (on tripod) in Tahoe National Forest to measure the distance and direction to trees. Researchers have found good agreement between Lidar and field measurements.**

Below, **a Pacific fisher on a den tree. Several studies have used Lidar to identify habitat characteristics that are important for wildlife.**

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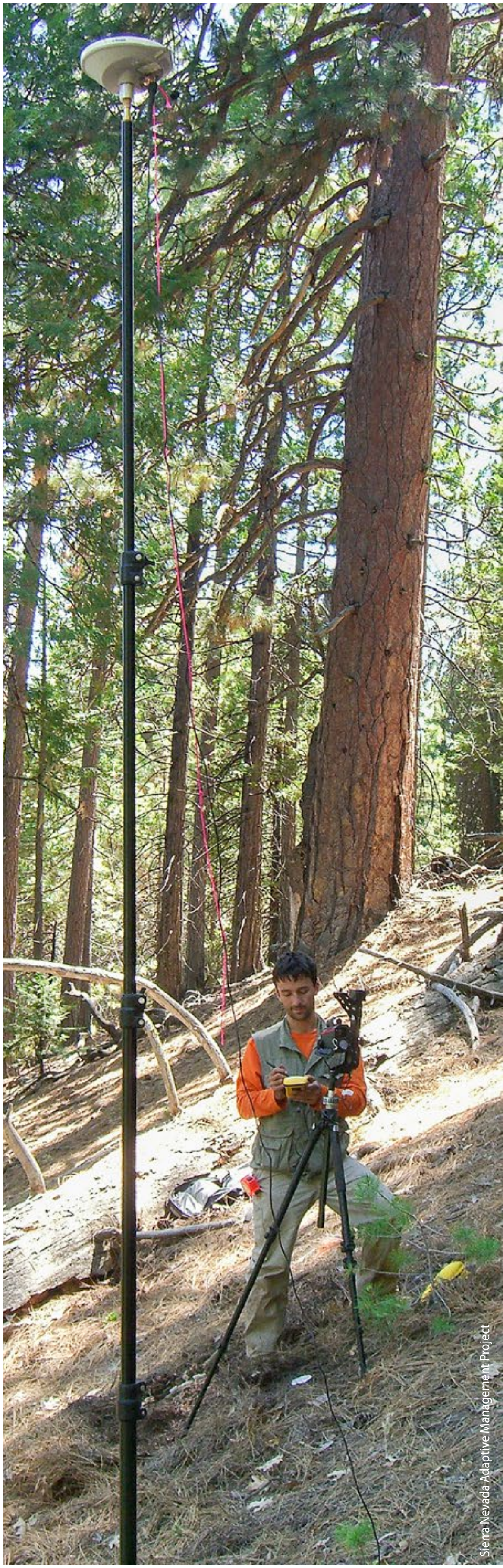

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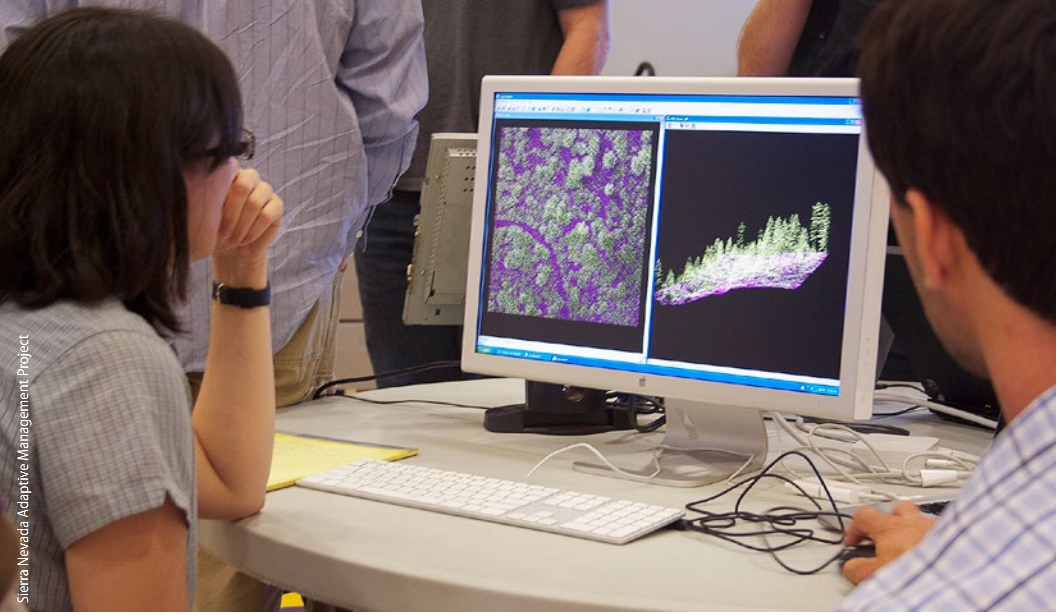

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Public workshops showing Lidar mapping capabilities have engaged members of the public, resource managers and staff from resource agencies. The adoption of Lidar in forest management is likely as the costs of the technology continue to drop.

canopy cover, crown base height and crown bulk density, as well as a layer describing the types of fuel found in the forest (called the fuel model). These spatial data layers are not often developed using Lidar data. Jakubowski, Guo, Collins et al. (2013) examined how well Lidar data could estimate them in the Tahoe National Forest. They found that tree height, canopy base height, canopy cover and general fuel types were predicted accurately using Lidar with multispectral images, but specific fuels were difficult to predict in dense forest (Jakubowski, Guo, Collins et al. 2013).

Downed logs on the forest floor, which provide fuel for forest fires, are a considerable challenge to map accurately. Blanchard et al. (2011) presented an object-based image analysis (OBIA) approach to delineate and classify downed logs using Lidar-derived metrics. Despite its success in identifying downed logs, the OBIA method requires significant analyst interpretation for classification, and so it can be considered a complement to field-based methods but not a replacement for them.

Downed logs on the forest floor, which provide fuel for forest fires, are a considerable challenge to map accurately.

Kane, North et al. (2013) used Lidar combined with Landsat data to examine the ecological relationships between differences in fire severity and the spatial structures of forests, defined as tree clumps and openings, for three forest types (ponderosa pine, white fir and sugar pine, and red fir). A complementary analysis was performed by Kane, Lutz et al. (2013), focusing on changes in canopy profiles after fires.

Biomass. Accurate measures and predictions of biomass are critical for estimating carbon storage on a stand and forest scale and also a global scale. Vegetation height metrics derived from Lidar are often used to predict biomass and have been found to provide accurate estimates of biomass even when forest density is high, because Lidar is not affected by the saturation problem associated with optical sensors, which can make moderate-density forests appear similar to high-density forests (Lu et al. 2012).

Hyde et al. (2006) compared the biomass estimation from Lidar, SAR/InSAR (a radar satellite), and ETM+ and Quickbird (optical sensors of moderate and high spatial resolution, respectively) and found that Lidar was the best single sensor for estimating biomass. Its higher accuracy in estimating biomass compared with Landsat TM and high-resolution Quickbird is also supported by Lu et al. (2012) and Gonzalez et al. (2010). Other studies focused on identifying methods to integrate Lidar with optical remote sensing (aerial and satellite images) to improve biomass estimation, given that biomass is related not only to tree structure, but also to factors strictly dependent on vegetation type (Chen et al. 2012), and optical remote sensing can provide information on vegetation type.

One way to incorporate vegetation-type information into biomass estimation is to stratify forest plots according to vegetation type and develop a separate statistical model for each type. This approach was taken by Swatantran et al. (2011), who used AVIRIS hyperspectral data to refine biomass prediction and showed that prediction by Lidar after species stratification from field data reduced errors by 12% compared with using Lidar metrics alone.

A different approach to biomass mapping was adopted by Chen et al. (2012), who used mixed-effects modeling to integrate airborne Lidar data and vegetation-type data derived from aerial imagery. Incorporating vegetation type improved biomass estimation (R^2 improved from 0.77 to 0.83) and decreased RMSE by 10% from 199.6 to 178.4 megagrams (Mg) per acre (80.8 to 72.2 Mg per hectare).

In contrast to Swatantran et al. (2011) and Chen et al. (2012), other studies suggest that integrating Lidar data and optical or radar imagery does not produce better biomass predictions. For example, Hyde et al. (2006) found that adding Quickbird and SAR/InSAR forest structure metrics to Lidar resulted in no improvement for estimating biomass across 120 circular 0.40-acre (1-hectare) plots in the Sierra National Forest; this was explained by the fact that the structure metrics from SAR/InSAR and Quickbird were very similar to those of Lidar.

All the studies reviewed here strongly agree that airborne Lidar data provides the most accurate estimates of forest biomass, but rigorous procedures should be taken in selecting appropriate allometric equations to use as reference biomass estimates (Zhao, Guo, Kelly 2012). Reference biomass is typically calculated using published allometric equations, such as national-scale equations (Jenkins et al. 2003) or equations from the Forest Inventory Analysis program (fia.fs.fed.us). Zhao, Guo, Kelly (2012) examined how the use of one or the other strongly influenced Lidar regression modeling results, and they suggest that in the mixed-conifer forests of the Sierra Nevada regional biomass equations should be preferred over national equations.

Terrain and infrastructure. Identifying road infrastructure is essential for wildland fire planning and suppression measures, and current geographic information system (GIS) data sets do not provide adequate and complete road inventories in many forests. Lidar data can be used to produce highly detailed digital terrain models (DTM) at fine (e.g., 3.3-feet, or 1-meter) resolutions (Guo et al. 2010), which can also provide detailed and accurate road inventories. White et al. (2010) showed the suitability of Lidar for mapping forest roads in the dense forest canopy and steep, complex terrain of the Santa Cruz Mountains. The study highlighted forest road features that are not visible through traditional remote sensing data such as satellite imagery and aerial photography because passive sensors are unable to penetrate dense canopy.

Future of Lidar

The future of Lidar for forest applications depends on a number of considerations, including costs, which have been declining; new developments to address limitations with discrete Lidar; and new methods to deal with increasing data size.

Costs. Adoption of Lidar in forest management has not been complete. Wynne (2006) says "small-footprint imaging Lidar systems now dominate much of forest remote sensing research, but have yet to be integrated into operational inventory and monitoring at the scale of management." Although this is changing, large-area forest monitoring and mapping activities with Lidar remain challenging due to costs, logistics and the data volumes involved (Wulder et al. 2012). While the cost of acquiring Lidar is still higher than for aerial or satellite imagery, a few studies suggest that Lidar data can be more cost effective than intensive fieldwork. Hummel et al. (2011) say: "We found that the accuracy and cost of a Lidar-based inventory summarized at the stand level were comparable to traditional stand exams for structural attributes. However, the Lidar data were able to provide information across a much larger area than the stand exams alone."

Two published studies present actual costs: Wulder et al. (2008) estimated a cost of ~ $1 per acre ($3 per hectare) for mapping with low-density (0.1 pulse per square foot, or 1 pulse per square meter) discrete Lidar data. Renslow et al. (2000) outlined a forest management scenario for a typical even-aged, managed forest of 500,000 acres in which 2% of 10,000 acres (200 acres, or 81 hectares) are sampled annually to determine what management steps are needed. Renslow et al. estimated that 14 weeks of traditional fieldwork would cost $32,000, or $160 per acre (~ $395 per hectare). In contrast, field data collection and collection and analysis of Lidar data would cost $16,600, or $83 per acre ($205 per hectare). However, these Lidar cost estimates are far higher than estimates of forest mapping with Landsat data, particularly since Landsat data is now free. Franklin et al. (2000) estimated ~ $0.15 per acre ($0.30 to $0.40 per hectare) in 2000 for mapping with Landsat imagery, drastically down from the costs in the 1980s, of ~ $1 per acre ($2 to $3 per hectare) (adjusted to 2000 dollars).

Lidar costs are declining, and there are potential savings for forest managers who wish to use Lidar data as long as they can focus on plot-level measurements (Jakubowski, Guo, Kelly 2013). With plot-level measurements, a forest manager can cover more of the forest for less cost than required for measurements of individual trees.

Limitations. There are known limitations to the use of discrete Lidar for forest mapping — in particular, smaller trees and understory are difficult to map reliably. In Washington state, Richardson and Moskal (2011) found unbiased density estimates for trees taller than 65 feet (20 meters) but underestimation of density in trees less tall than that. Similarly, Jakubowski, Guo, Collins et al. (2013) found that the accuracy of stand structure metric predictions generally decreased with increased canopy penetration; measures at the top of the canopy (e.g., canopy cover, height) were more accurate than those near the forest floor (e.g., shrub height, fuel loads). This limitation is reported elsewhere, but in the next 5 years, it will become less relevant as waveform data becomes more common than discrete data and researchers have a chance to evaluate waveform data with information from the field.

Data size. The benefits of forest mapping with moderate-scale satellite imagery such as Landsat are immense: inexpensive cost, with large and repeat views, and detailed depictions of forest cover and type. But there are drawbacks to Landsat that Lidar does not have. With Lidar, the effective scale and resolution are not chosen a priori for the analyst, as is the case with satellite imagery. The pixel as a sample has been called problematic since the 1990s (Cracknell 1998; Fisher 1997); pixels can be too large to capture detail and their placement depends on the satellite's orbit. In contrast, a Lidar point cloud can be resolved into any number of operational resolutions for integration with other mapped products or field data.

Representation is critical: A 12-acre (5-hectare) forest stand, for example, can be represented by 55 data points (e.g., Landsat, 98.4 feet, or 30 meters) and likely undersampled for many purposes or by 2 million data points (e.g., a Lidar point cloud) (table 2), which can then be resolved into a collection of height profiles, structural metrics, individual trees or products of any spatial resolution (e.g., 1 to 100 feet). This flexibility in representation can be both a benefit and a challenge, as increased data points and multiple scales of representation require more

TABLE 2. Data collection details and approximate data size of a 12.35-acre (5-hectare) forest stand by various remote sensing systems

Landsat TM (30 m pixel)	Landsat ETM (15 m pixel)*	SPOT (10 m pixel)	IKONOS (1 m pixel)	Lidar (1 pulse/m, 4 returns)	Lidar (10 pulses/m, 4 returns)
~ 55 pixels (330 bytes)	~ 222 pixels (1.3 Kb)	500 pixels (2 Kb)	50,000 pixels (390 Kb)	200,000 points (5 Mb)†	2,000,000 points (50 Mb)

Source: Modified from Wulder et al. 2012.

* Panchromatic or pan sharpened.

† Lidar file sizes are approximate and vary with compression format.

complex software and data storage options (Wulder et al. 2012).

Our review of Lidar research illustrates a preponderance of studies of conifer forests in California; in the future we will likely see more use of Lidar in oaks and redwood forests as managers continue to expand their use of these data and focus on more ecosystems. As Lidar costs continue to decline and new and easier methods are developed to process the data, it is possible that managers will incorporate Lidar data in forest management, particularly where detailed information on forest structure is required across large spatial scales. CA a

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Carbon calculator tracks the climate benefits of managed private forests

by William C. Stewart *and* Benktesh D. Sharma

As part of California's strategy to reduce greenhouse gas emissions, private forest landowners are now required to address carbon sequestration as a management goal when submitting timber harvest plans. Using public data on forests and forest products, we developed a calculator that tracks the carbon sequestration benefits related to live trees, wood used for bioenergy and wood going into products. The calculator is adapted for different forest types, forest management techniques and time frames. Based on current best practices used in California, we estimate that harvested and regenerated forests will provide approximately 30% more total carbon sequestration benefits than forests left to grow for an equal time. More than half of the total benefits relate to harvested wood substituting for fossil fuels and fossil fuel–intensive materials such as cement and steel. With relatively efficient management practices, harvesting a ton of wood provides more sequestration benefits than leaving that ton growing in the forest.

It is well documented that very limited progress has been made at the global level to reduce greenhouse gas emissions and that geoengineering technologies will be insufficient to reverse the trend of rising emissions (Nordhaus 2013). However, there is progress at the state level. As it implements the California Global Warming Solutions Act of 2006 (AB 32), California is taking the lead in this country in promoting innovative approaches to emission reductions and mitigation measures. One potentially cost-effective mitigation measure is the maintenance and enhancement of carbon sequestration in forests and forest products (Joyce et al. 2014; Smith et al. 2009).

How to compare the climate benefits of joint use and no-harvest forest management approaches is being debated. Some researchers suggest that the "joint use of carbon sequestration and the provision of forest-derived products (e.g., timber and biomass for energy) will optimize the contribution of forestry in climate mitigation" (Canadell and Raupach 2008). Researchers who ignore the climate benefits related to forest products often conclude that a no-harvest approach is preferable.

There is no consistent approach for counting carbon sequestration benefits of forests and forest products in global, federal and state inventory systems. At the global level, benefits are covered in three different sections of national greenhouse gas inventories: agriculture, forests and other land uses (AFOLU); energy systems; and buildings (IPCC 2006). At the federal level, greenhouse gas inventories, emissions and net sequestration are tracked for forests, wood products in use and wood products deposited in landfills. Emissions from wood used for bioenergy are not included in national emission totals since they reduce the need to burn fossil fuels (US EPA 2014). Sequestration benefits of using wood for bioenergy depend on fossil fuel displacement and how the bioenergy utilization is integrated with overall forest management (Malmsheimer et al. 2011; Smyth et al. 2014). At the state level, California's 2014 Climate Change Scoping Plan mentions the positive benefits of using more wood products in construction and more wood chips to generate energy, but the accounting framework and recommended policies focus only on increasing carbon inventories in the forest (California Air Resources Board 2014).


Robert York

UC researchers have developed a tool that helps users understand how forest management options will affect carbon sequestration. *Above,* managed stands of mixed-conifer forest in the Sierra Nevada.

Online: http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v069n01p21&fulltext=yes

doi: 10.3733/ca.v069n01p21

The increase in carbon stands over time in a let-grow forest, *above*, is based on the observed rate of live tree carbon by stand age.

Foresters who submit timber harvest plans in California face the challenge of demonstrating compliance with California's numerous climate-oriented laws even though different carbon accounting systems can produce conflicting results and the relevant laws are complex in their aims. In 2010, AB 1504 revised the intent of the Z'Berg Nejedly Forest Practices Act regulating nonfederal forest lands to ensure both of these goals: "(a) Where feasible, the productivity of timberlands is restored, enhanced, and maintained. (b) The goal of maximum sustained production of high-quality timber products is achieved while giving consideration to values relating to sequestration of carbon dioxide, recreation, watershed, wildlife, range and forage, fisheries, regional economic vitality, employment, and aesthetic enjoyment" (California Code of Regulations 2010). In addition, the state's forests are diverse; they vary considerably in terms of dominant tree species, ownership and productivity (table 1).

Developing a calculator

To help forest landowners describe how a managed forest meets the goals of the Forest Practices Act, we developed a carbon calculator to document the climate benefits of a forest and any harvested forest products. To be relevant for both submitters and regulators, the calculator covers a range of forest types, forest management options and products. We used current publicly available information and presented the carbon calculation in a disaggregated format so that submitters, regulators and other interested parties can see how it is achieved.

To project forest carbon inventories over long time periods with significant but unknown probabilities of disturbance losses, we used the Carbon Online Estimator (COLE) growth model (Van Deusen and Heath 2014). This free Web-based tool allows users to create and download reports summarizing carbon sequestration in U.S. Forest Service forest inventory and analysis (FIA) plots.

We used tree growth data from nearly 2,000 FIA plots on private and federal lands to generate reports for California's four major timberland types — mixed conifers, ponderosa pine, Douglas fir and redwood. We then used Von Bertalanffy growth equations (Van Deusen and Heath 2014) for each forest type to model live tree carbon. The trajectory of a let-grow forest — one that is not harvested but left to grow — is based on the observed rate of live tree carbon by stand age. It illustrates a slowing growth rate of net aboveground carbon sequestration as the forest ages.

To estimate the sequestration benefits associated with harvested products, we used the most current state and regional information on where harvested wood goes (Morgan et al. 2012) and how products are used (McKeever and Howard 2011; Sathre and O'Connor 2010; Skog 2008; Smith et al. 2009). Stewart and Nakamura (2012) used these same sources and estimated that the sequestration benefits of harvested wood were two times (when wood used for bioenergy is

TABLE 1. Area of timberland, number of FIA plots and average site productivity for four California major forest types

	Mixed conifers	Ponderosa pine	Douglas fir	Redwood
Area (acres)	6,359,900	1,946,700	942,600	592,200
All FIA plots (no.)	1,374	263	187	118
Private FIA plots (no.)	351	112	101	95
Average productivity (cubic feet/acre/year)	103	77	115	180

considered) to four times (when bioenergy use is not considered) larger than those estimated by models such as the greenhouse gas emission calculator developed by the California Department of Forestry and Fire Protection (Cal Fire 2010) that use the older estimates from Smith et al. (2006).

All forest carbon that is cut at harvest was accounted for as logging slash left, logging slash used for energy, mill residues used for energy, wood products and mill waste. The regenerated forest was then modeled with the Von Bertalanffy growth coefficients based on relevant private forest plots, where competing vegetation is controlled. The emissions related to fossil fuel energy used in the harvest operations were estimated as 3% of the total energy value of the harvest based on Wihersaari (2005) and subtracted to generate a net carbon sequestration value for the harvest operations.

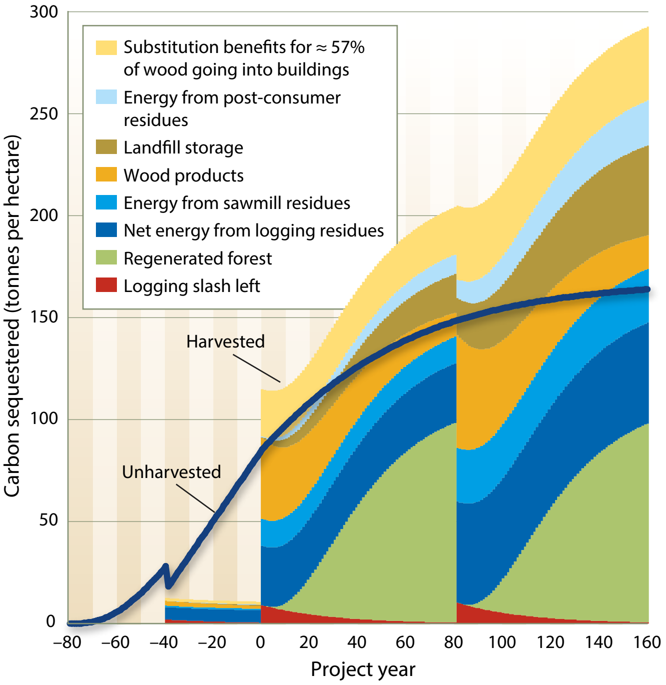
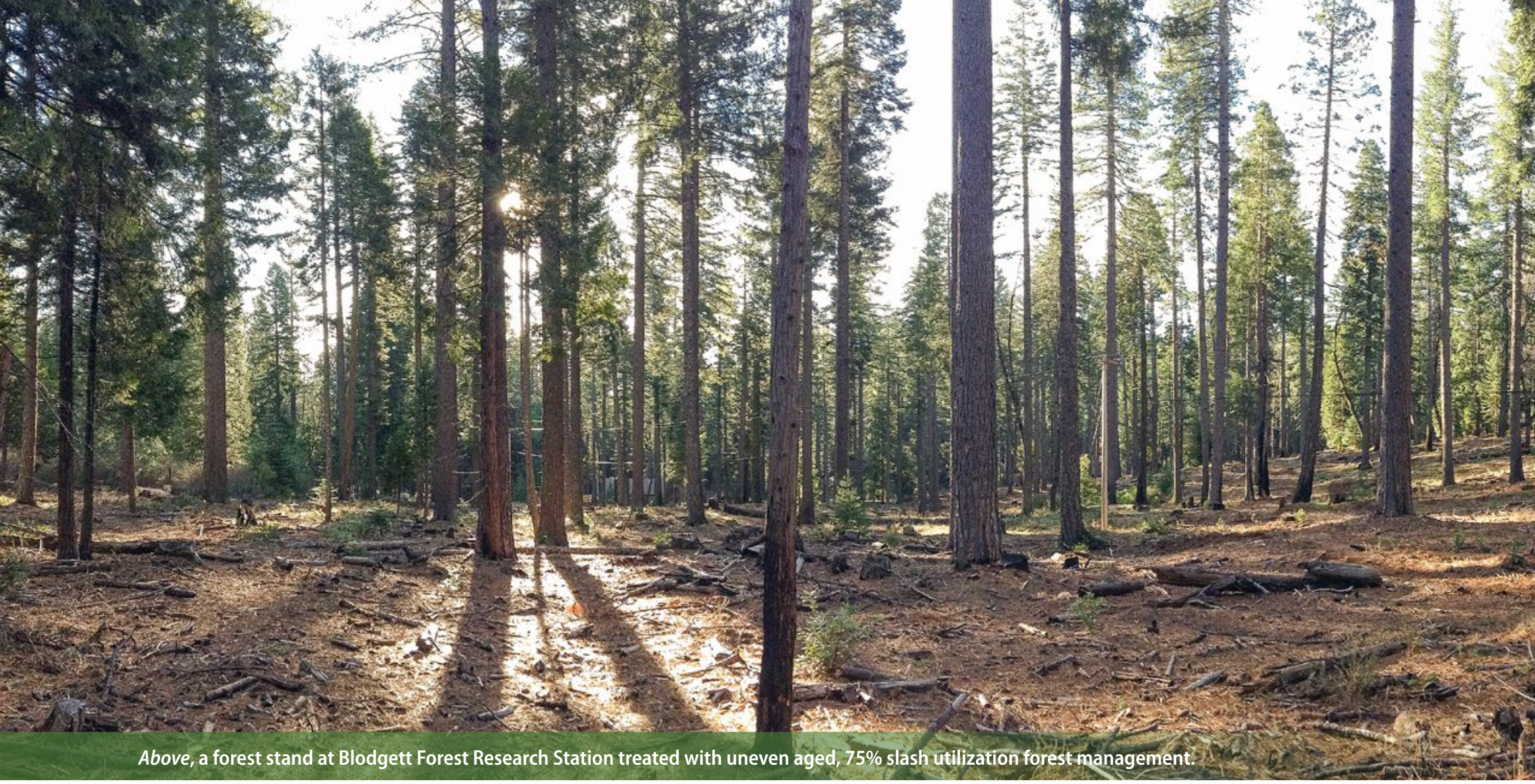


Fig. 1. Cumulative sequestration benefits over time from 1 hectare of a mixed-conifer forest under two scenarios: unharvested (or let-grow), and even-aged harvest and regeneration with 75% of slash (logging residues) used for energy at a harvest at year 0. The life cycle includes the 80 years since the forest started from seedlings as well as two cycles of harvesting and replanting.

We used the best practices assumption of 75% slash utilization for delivery to wood-fired energy plants with the remainder left to slowly decompose on site. This is lower than the sample of projects in Northern California documented by Stewart and Nakamura (2012) but higher than the 66% used by Ince et al. (2011). We provided variants with 0% and 25% slash utilization since recent closures of some wood-fired energy plants due to insufficient payments for the wholesale electricity warrant modeling lower collection rate estimates.

Our modeling tracked wood products through sawmills and energy plants, drawing on published allocation of products and conversion efficiencies (Christensen et al. 2008; Morgan et al. 2012). Our 45-year half-life for wood products produced in California was based on the weighted combination of a 60-year half-life for lumber products (McKeever and Howard 2011; Skog 2008) and a 15-year half-life for other products that is proportional to the allocation in California (Morgan et al. 2012). According to McKeever and Howard (2011), 57% of California's lumber products go into buildings, where the wood is estimated to provide additional carbon sequestration benefits and energy savings by displacing fossil fuel alternatives (Sathre and O'Connor 2010). The estimated allocation of postconsumer wood residues between landfills, energy and uncollected waste was based on estimates by Stewart and Nakamura (2012) of current best practices in California; undoubtedly these could



Above, a forest stand at Blodgett Forest Research Station treated with uneven aged, 75% slash utilization forest management.

improve with better technologies and financial incentives.

To conform with the units used in COLE reports (Van Deusen and Heath 2014), we used a single hectare (2.47 acres) as the unit of analysis. We modeled different actions on an 80-year-old forest that had been treated with a light commercial thin 40 years earlier. The regenerating forest as well as the products were then tracked for 40 years, 80 years (approximately the half-life of wood used in single family homes (Skog 2008)) and 160 years to illustrate how the length of the analysis affected the climate benefit comparisons.

As noted earlier, uncertainty remains on how to account for future rates of forest growth as well as climate benefits that accrue outside of the forest sector related to using wood products and bioenergy rather than fossil fuel–intensive products such as cement, steel, coal and natural gas (Smyth et al. 2014). We cannot accurately predict how future forest growth rates will compare to the historic rates used in the calculator. We also did not include any probability of stand-terminating disturbances such as wildfires or insect outbreaks that would reduce long-term carbon sequestration. Different building rating systems such as LEED and Green Globe use various methods to estimate the carbon footprint of using wood rather than concrete in buildings. Depending on the location of a forest project, the ability to sell the slash for bioenergy in the future may be limited if the goals of California's 2012 Bioenergy Action Plan are not achieved.

Using the calculator

In 2013, we expanded the carbon sequestration model submitted with our 2011 timber harvest plan for the mixed-conifer forests at the UC Blodgett Forest Research Station (University of California 2014) to cover more forest types and more management options. The current tool and a user guide are posted on UC's Forest Research and Outreach website (UCCE 2014). The user's first step is to choose a forest type that best matches the area in the user's proposed timber harvest plan. After choosing the relevant forest type, users can review worksheets with detailed forest growth and product life cycle information based on published literature to choose the relevant factors to match their plan. If desired, the user can alter any of the input coefficients to customize the output.

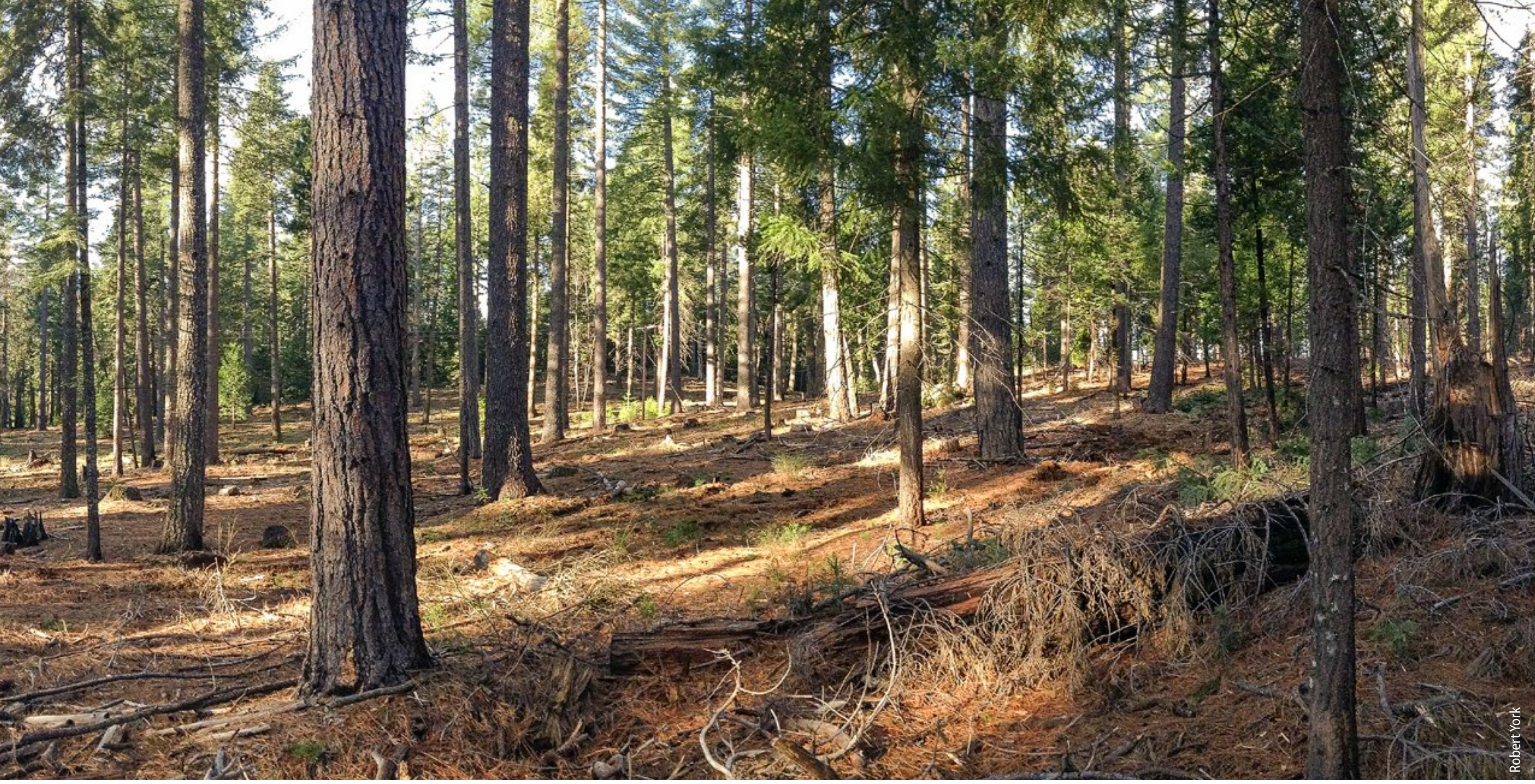
The next step is to choose the forest management option that best matches the user's situation. A let-grow alternative is included with each option to provide a harvest/no-harvest comparison. Tables and figures in the upper left section of each management option worksheet summarize the input coefficients as well as the results.

Users can estimate the total sequestration for their timber harvest plan by multiplying the area of the most relevant harvest type by the relevant coefficients. Carbon quantities should be multiplied by 3.67 to provide measurements in standardized tons of carbon dioxide used in emission-based accounting systems.

A review of a forest project example demonstrates the results a forester can gain by using the calculator to estimate the net climate benefits associated with a timber harvest plan. Figure 1 shows the

TABLE 2. Components of the cumulative life cycle carbon sequestration benefits, averaged over 160 years, of mixed-conifer forest under two management scenarios

Scenario (in both, trees start as new seedlings)	Live trees	Wood products	Bioenergy	Landfill storage	Building product substitution	Total benefits
	tonnes of carbon per hectare					
Let-grow	77	0	0	0	0	77
Harvested and regenerated	43	12	26	6	12	99


Robert York

carbon sequestration in a mixed-conifer forest under two scenarios: unharvested (or let-grow) and an even-aged harvest and regeneration option with 75% of slash (logging residues) used for energy. The solid blue line models the predicted rate of carbon sequestration in live trees for the unharvested forest based on the COLE forest growth model. The stacked columns show the carbon sequestration of the harvested forest — the regenerated forest (also modeled with the COLE forest growth model) plus the sequestration benefits associated with the harvested products.

Table 2 compares the cumulative carbon sequestration benefits of the two scenarios for 160 years starting from new tree seedlings. The harvested scenario includes a commercial thin at 40 years, a final harvest at 80 years, and regeneration of the forest for 80 more years. The harvested forest has lower average sequestration benefits in the live trees but greater overall sequestration benefits when the harvested products are considered.

Table 3 summarizes our best practices estimate of annual carbon sequestration rates for four forest types, five management options and three time periods. The more productive redwood and Douglas fir forests sequester considerably more carbon than the mixed-conifer and ponderosa pine forests. Efficient utilization of harvested products increases overall sequestration benefits across all forest types and time periods.

More benefits in joint use

Managed (harvested and regenerated) forests provide more carbon sequestration benefits than let-grow forests when the benefits of the harvested products are accounted for. Table 4 summarizes the relative carbon sequestration benefits of let-grow forests and managed forests weighted by the total area of private

TABLE 3. Cumulative life cycle carbon sequestration benefits, averaged over 120, 160 and 240 years, for four forest types and five management options

Management, logging residue utilization	Mixed conifers			Ponderosa pine			Douglas fir			Redwood		
	Time frames (years)											
	120	160	240	120	160	240	120	160	240	120	160	240
	tonnes of carbon per hectare											
Let-grow	56	77	104	51	60	69	125	154	187	156	213	288
Even aged, 0%	63	87	126	66	85	114	153	203	278	166	226	322
Even aged, 25%	65	91	134	69	89	121	159	213	295	173	237	342
Even aged, 75%	70	99	149	74	98	135	171	233	329	185	260	383
Uneven aged, 75%	70	103	166	71	95	142	167	233	362	194	283	458

TABLE 4. Ratio of sequestration benefits of managed (harvested and regenerated) forests compared to let-grow forests for 40, 80 and 160 years after initial harvest of a mature forest stand

Management, logging residue utilization	Years after harvest		
	40	80	160
Let-grow baseline	1.00	1.00	1.00
Even aged, 0%	1.15	1.18	1.28
Even aged, 25%	1.19	1.24	1.36
Even aged, 75%	1.28	1.35	1.51
Uneven aged, 75%	1.28	1.40	1.70
Four-treatment average	1.23	1.29	1.46

forests in California. If all carbon sequestration benefits are counted, we project that California's private forests that are harvested and regrown for another 80 years will provide approximately 30% more total carbon sequestration benefits than forests left to grow for 80 years. The relative advantage of the managed forest over the let-grow forest is slightly less for shorter timeframes and slightly greater for longer timeframes. Expanded residue utilization for bioenergy increases total sequestration benefits compared with leaving slash to decompose in the forest. The increased benefits resulting from uneven-aged management systems compared with even-aged management are smaller than the increased benefits related to more slash utilization.

The carbon calculator helps users understand how forest management options will affect carbon sequestration. It can be used anywhere in the United States where relevant FIA plot data is available. And its assumptions, inputs and coefficients can be changed to match the analytical needs of regulators and submitters. The carbon sequestration categories we presented here match up well with the U.S. Greenhouse Gas Inventory (US EPA 2014) in terms of tracking carbon in live trees, forest products and landfills, and bioenergy. Under the relatively efficient management practices currently used by private forest owners in California and depending on what percentage of logging residues are used for bioenergy, calculations show that a ton of harvested wood provides slightly more or significantly more sequestration benefits than leaving that ton in the forest.

The calculator's simple and transparent format can improve the regulatory review process for forest landowner's compliance with legislation designed to reduce California's greenhouse gas emissions. It is also a useful tool for assessing forest management options in private and federal forests. CA

Harvested and regenerated forests provide more carbon sequestration benefits than let-grow forests when the benefits of the harvested products are accounted for.

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Large-tree removal in a mixed-conifer forest halves productivity and increases white fir

by Robert A. York

Removing all large trees without planning to replace them with either planted or naturally regenerated younger trees (i.e., high-grading) is widely thought to have negative consequences on a forest's productivity and species composition, but no previous studies in California had evaluated this assumption. To make such an evaluation, I measured productivity and canopy species composition shifts following the repeated removal of large trees and compared the results with those from two other basic forest harvest methods: thinning from below and single tree selection. Timber productivity was substantially lower with large-tree removal (0.65 thousand board feet per acre per year) than with the other methods (averaging 1.33 thousand board feet per acre per year), which included the no-harvest control, where yield was zero. Large-tree removal also resulted in more species change, with white fir increasing in the canopy and ponderosa pine decreasing.

Large trees in forests are highly valued, often because of their ecological roles in sustaining wildlife habitat and biodiversity (Franklin et al. 2002). Their size, however, also makes them highly valued for timber because of their high wood quality and the considerable gains in logging efficiency and volume production when harvesting large logs. In many Western forests, a variety of regulatory, economic and ecological factors (e.g., threats of large-tree harvest limits, lumber demand and competition-related mortality) have made large trees more rare than they were a century ago (Hagmann et al. 2013; Lutz et al. 2009). The repeated harvest of the majority of large trees in a stand without steps to replace them obviously contributes to this large-tree scarcity.

Repeated large-tree removal is an especially attractive harvesting practice in forests on nonindustrial private lands, where timber revenue can be marginal because of the small scale of harvests. Removing large trees can make a harvesting operation much more feasible and profitable in the short run; the level of expertise needed for tree marking is low and the yield per tree is high. Logging efficiency is therefore maximized and harvest costs are lower. However, there are potential negative long-term effects of large-tree removal, including the impacts on wildlife and biodiversity and also on timber productivity and the tree species composition of the forest. Because of the relatively high volume production of large trees (e.g., Stephenson et al. 2014), removing only large trees may result in a net decline in stand-level volume growth and therefore a decline in merchantable volume (timber production) over time. The removal of large trees may also cause genetic bottlenecking if they are from the same cohort as the smaller trees that are left behind and the smaller trees are genetically predisposed for slower growth.

Timber management on nonindustrial lands in California rose steadily between 2000 and 2010 (Cal Fire 2010), and recent legislation that expands the acreage limits for nonindustrial harvest planning (Assembly Bill 904) could significantly increase harvest activity. This trend makes clear the need to understand the

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Despite the potential for long-term negative impacts, large-tree removal is still common throughout the United States. *Right*, a typical stand where most large trees have been removed, leaving only small- and medium-sized trees behind.

Will Suckow

tradeoffs between different management approaches on these lands.

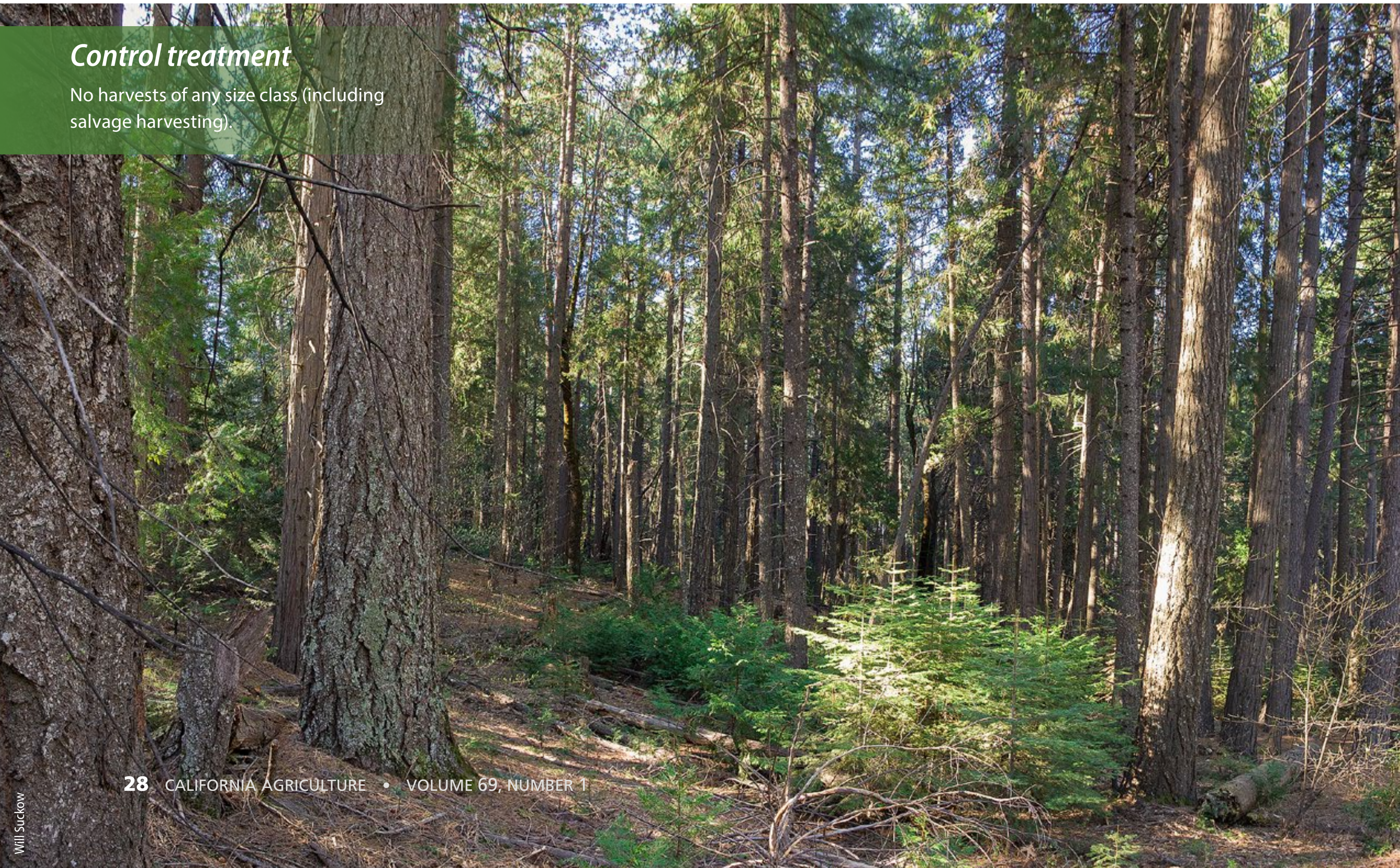
This study addresses the consequences of repeated large-tree removal compared to those of three other timber harvesting methods (thinning from below, single tree selection, and no harvests). I define large-tree removal as cutting all or most trees above a specified tree size (typically, a specific diameter at breast height, or DBH) and leaving all trees of smaller size. Various regional and technical terms have been used to describe this method of harvesting, including diameter limit cutting, thinning from above, overstory removal and the more pejorative terms high-grading and dysgenic selection. Clear-fell harvesting, which removes trees of all size classes including large trees, is a different form of harvesting and is not addressed here.

Despite a history of exploitative practices that focused on the cutting of the largest trees and the potential for long-term negative impacts, large-tree removal is still common throughout the United States. In hardwood forests of the Northeastern states, for example, studies highlight the benefits of large-tree removal, including its relative simplicity in terms of implementation ("cut all trees greater than 24 inches DBH"), its economic advantages and even the ecological gains related to forest health (Buongiorno et al. 2009). Managers in this region also understand the negative effects of large-tree removal because of the empirical studies that have tracked species composition and productivity effects (Angers et al. 2005; Erickson et al. 1990; Hawley et al. 2005; Kenefic et al. 2005; Kern et al. 2006).

Prior to this study, however, no such exploration of the effects of large-tree removal had been done in California forests. Some regulations that limit large-tree removal in California are in place. For example, there are restrictions on cutting trees greater than 30 inches DBH on many federal forestlands, and permits for selective harvests on private lands require that trees greater than 18 inches DBH constitute a minimum amount of basal area (the cross sectional area of stems at breast height) per acre. Very little published evidence from experimental trials exists to back up claims of the negative or positive effects of large-tree removal on productivity and species composition. I address the need for more information by reporting results from a long-term study at Blodgett Forest Research Station (BFRS) designed to compare repeated large-tree removal with three harvesting methods that maintain a relatively intact canopy over time: removing only smaller trees, selecting trees of all size classes, and not removing any trees.

Sierra Nevada study area

BFRS is on the western slope of the central Sierra Nevada in California (38º52′ north latitude and 120º40′ west longitude); the elevation is 4,260 feet (1,298 meters). The climate is Mediterranean, with dry, warm summers and mild winters. Average monthly maximum temperatures during the summer months is 79°F (26°C); average monthly minimum temperatures during winter months is 34°F (1°C) over the past 30 years measured on-site. Annual precipitation averages 65 inches (165 centimeters), most coming from rainfall during fall and spring months. Before the imposition of fire suppression policies, the median fire interval in the area was 9 to 15 years (Stephens and Collins 2004). In general, slopes are less than 30%. The



Control treatment

No harvests of any size class (including salvage harvesting).

Will Suckow

soil developed from granodiorite parent material and is productive for the region. Heights of codominant canopy trees typically reach 89 to 112 feet (27 to 34 meters) in 50 to 60 years.

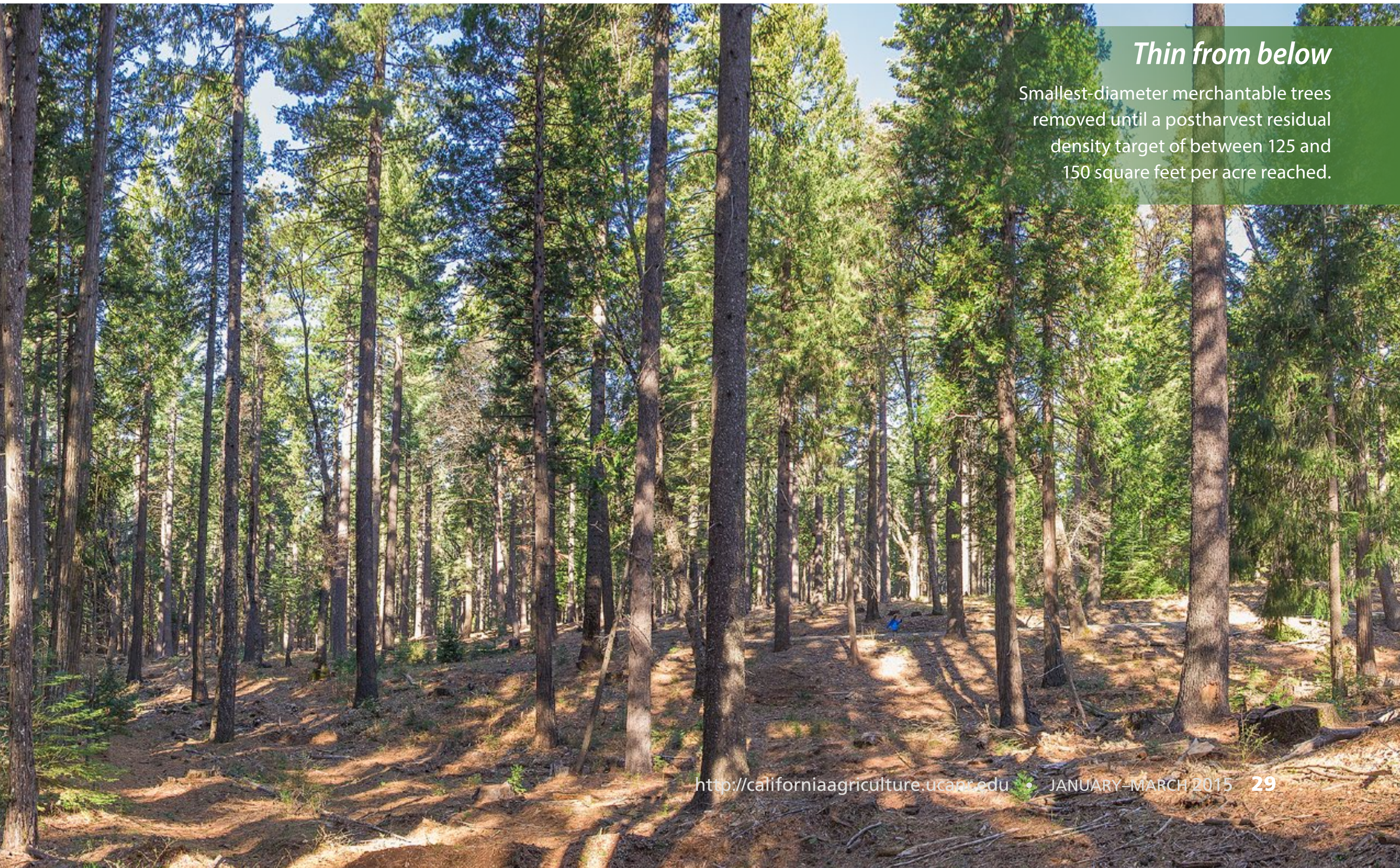
Vegetation at BFRS is dominated by a mixed-conifer forest type (Barbour et al. 2007) composed of variable proportions of white fir (*Abies concolor*), incense cedar (*Calocedrus decurrens*), Douglas fir (*Pseudotsuga menziesii*), sugar pine (*Pinus lambertiana*), ponderosa pine (*Pinus ponderosa*) and California black oak (*Quercus kelloggii*). Like much of the mixed-conifer forest in the Sierra Nevada, the study area was clear-fell harvested for timber extraction in the early 1900s, and the subsequent forest developed from sparse residual trees and advanced regeneration. By 1980, the beginning of the period used for this study, stands were comprised of continuous tree canopies of mixed species (i.e., structures were typical of second-growth forests).

Treatments for this study were located throughout the ~ 2,900 acres (1,734 hectares) of the BFRS main tract. In the 1970s, BFRS was allocated into managed stands, the boundaries of which were formed by small drainages and ridges. These stands were assigned to various management strategies to represent a broad gradient of silvicultural practices, and each stand has been managed with the same treatment regime consistently over time. The same manager wrote harvest prescriptions throughout the time period used for this study (1980 to 2006), and the same equipment operator was used for all logging.

Four harvest strategies

Four continuous cover harvesting strategies are reported on in this study to represent the options that private landowners have when the primary objective is to generate periodic timber revenue while maintaining continuous canopy cover. Maintaining continuous canopy cover may be done to meet aesthetic and wildlife habitat objectives, or it may be required by easements or constraints from permitted nonindustrial management plans. The four study treatments were as follows:

1. A control treatment with no harvests of any size class (including salvage harvesting).
2. Large-tree removal: The largest-diameter trees were preferentially removed until a postharvest residual density target of between 125 and 150 square feet per acre (29 and 34 square meters per hectare) was reached. Re-entry (the next harvest) occurred when density reached approximately 200 to 250 square feet per acre (46 to 57 square meters per hectare).
3. Thinning from below: The smallest-diameter merchantable trees were removed until a postharvest residual density target of between 125 and 150 square feet per acre was reached. Re-entry occurred when density reached approximately 200 to 250 square feet per acre.
4. Single tree selection: Trees of all size classes were removed, in rough proportion to the stand-level density of different size classes before harvest. All size classes were maintained over time. Postharvest residual density was approximately 100 to 125 square feet per acre (23 to 29 square meters per hectare). Re-entry occurred when density reached approximately 200 to 250 square feet per acre.



Thin from below

Smallest-diameter merchantable trees removed until a postharvest residual density target of between 125 and 150 square feet per acre reached.

Is high-grading common in California?

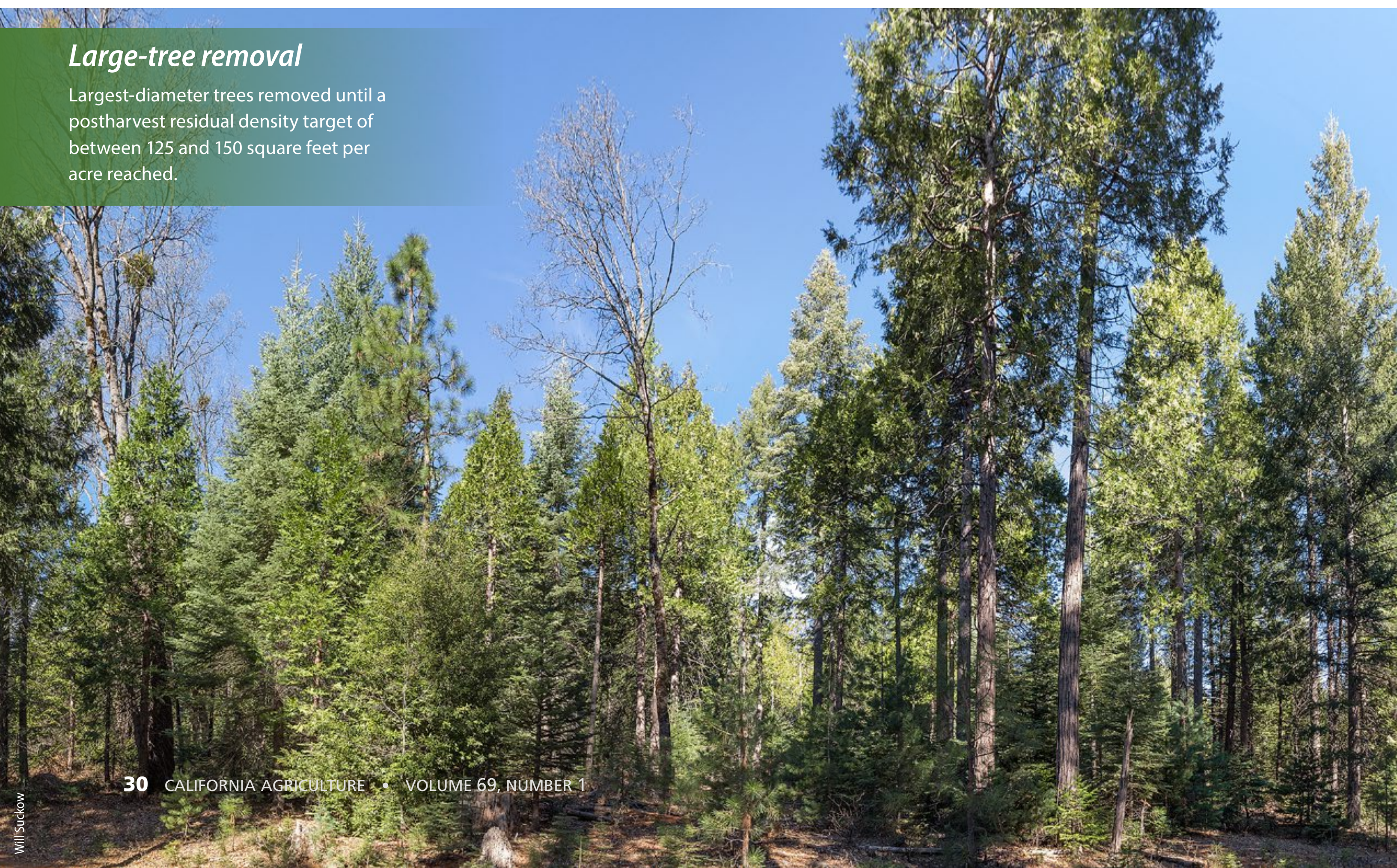
The harvest treatments at BFRS are done within the bounds of the regulations governing commercial timber harvests on private lands, the California Forest Practice Rules. The rules do not define high-grading, per se. They do, however, define shelterwood removal, which was the method applied in order to remove large trees preferentially for this study.

Shelterwood removal traditionally refers to the removal of a low-density overstory of large trees, but only after a younger cohort has been established in the understory by a very heavy thinning from below (i.e., the shelterwood seed step). The large tree removal done for this study was essentially a shelterwood removal without a preceeding shelterwood seed step. A treatment that combines a shelterwood seed step with a removal step is similar to even-aged harvests such as clearcuts with respect to the resulting forest structure and composition. Because there is no requirement on private lands in California to show that larger trees are any older than mid- or understory trees, however, shelterwood removal can be used as a means to simply harvest all large trees (i.e., to high-grade), without taking account of whether remaining trees are a younger cohort of the large trees or simply slower-growing trees of the same age.

The second large-tree removal harvest done for this study happened before regulations were changed in the mid-1990s, which allowed the shelterwood removal method only once in the lifetime of a stand. The dramatic decrease in productivity observed after only two harvests in the study brings up a reasonable question: Is even one round of high-grading (i.e., shelterwood removal without a preceding seed step) too many? If so, confirming with sample cores that the larger trees in the overstory are in fact the predecessors of the trees being left behind is a simple way to ensure that the shelterwood removal method does not simply become a vehicle for high-grading.

To explore if the shelterwood removal method was commonly used according to the textbook sequencing (heavy thin from below, cohort establishment and then overstory removal), and not in a way that led to high-grading, I queried the timber harvest plans in California between 2000 and 2013 (unpublished Cal Fire data). If shelterwood removals were done after a new cohort had been established, then there should be a roughly similar number of acres harvested with the shelterwood seed step as acres harvested with the shelterwood removal step. Surprisingly, approximately 11,000 acres (4,451 hectares) were planned for shelterwood removal against only 600 acres (243 hectares) for shelterwood seed step.

Compared to other methods (i.e., clearcut, selection, commercial thin), shelterwood removal is relatively rare on private forestlands. But the near absence of seed step harvests suggests that when the shelterwood removal method is used, it is not typically done in a planned sequence of treatments to regenerate stands. Some situations, such as the removal of legacy trees when there is an objective of having a young even-aged stand, may be justifiable, and may account for some of the acres that had no seed step. Closer examinations of shelterwood removal harvests — their intent and how they are carried out — may be worthwhile given the results of this study and the clear pattern of removing overstory trees without the preceding preparatory steps.



Large-tree removal

Largest-diameter trees removed until a postharvest residual density target of between 125 and 150 square feet per acre reached.

Will Suckow

The major difference between these treatments was simply the choice of tree size when selecting trees for removal. After harvests, the stocking level (residual density) was similar among harvested treatments, and the stocking level that triggered the next harvest was the same. Three stands for each treatment were used. Selected stands were similar in composition and structure at the time of the first harvest. The study period varied for each stand, depending on the timing of the first harvest and subsequent measurements. For the harvested stands, the study period included two harvests and at least 10 years of growth. The shortest interval was 10 years and the longest was 24 years. There were no significant differences in stand size (the average was 42 acres, 17 hectares), initial stocking of commercial volume (31.6 thousand board feet per acre) or study period (18 years) between the treatments (tested with a one-way ANOVA).

Measuring growth and yield

In each stand, growth and yield data were obtained from plots that are being permanently monitored by BFRS staff; the plots were established prior to and maintained throughout the study period. Plots are circular, fixed radius and 1/10 acre (0.04 hectare) in size. Plots in all stands are located on an ~ 400-by-400-foot (122-by-122-meter) square grid. Sampling intensity is approximately 2.8% of the stand area. On all plots, trees greater than 4.5 inches (11.4 centimeters) DBH are tagged and tracked over time. Tree measurement variables include species, DBH, total height, and height to live crown. Plots are measured within 1 year following harvest to account for changes caused by harvest activity. Recruitment into the 4.5-inch DBH size minimum is also recorded during each measurement. Plots are measured at least every 5 years in stands that are harvested periodically and at least every 10 years in control stands (no harvests).

For analysis, plots were averaged for each stand and then analyzed at the stand level ($n = 3$ for each treatment). The volume of all trees that were merchantable in size, > 10 inches (25.4 centimeters) DBH, was calculated from DBH and height measurements using equations in the growth simulator CACTOS (California Conifer Timber Output Simulator) (Wensel et al. 1986). CACTOS is the industry standard for projecting growth and yield in mixed-conifer forests in California. It was used to calculate merchantable volume (i.e., board foot volume) and stem volume (cubic feet). CACTOS was also used to "grow" plots when the most recent measurement occurred more than 1 year before the harvest; for example, if a measurement occurred in 1980 and the next harvest was in 1985, the measurement data were grown for 5 years to get the most accurate estimate of preharvest volume.

The growth of standing tree volume and the harvested volume (yield) were added together in order to compare net timber productivity among treatments. Volume productivity was expressed both in terms of merchantable volume (thousand board feet per acre) and in terms of total stem volume (cubic feet per acre; to convert cubic feet per acre to cubic meters per hectare, multiply by 0.07). I calculated net volume growth by subtracting stand-level volume before the first harvest from stand volume at the end of the final harvest. If a tree died between

Single-tree selection

Trees of all size classes removed in rough proportion to stand-level density of different size classes before harvest; postharvest residual density approximately 100 to 125 square feet per acre.

Will Suckow

measurements, its volume did not contribute to the second measurement. For the control stands, I used the time between measurements that most closely matched the time between measurements from the harvested stands. In the harvested stands, net volume was sometimes negative if standing postharvest volume after the second harvest was less than standing volume prior to the first harvest. For the controls, net volume was always positive because these second-growth stands are still aggrading following regeneration harvests a century ago (Eitzel et al. 2013).

Harvested yield was calculated from the plot measurements, which were always done immediately following harvests. During postharvest surveys, trees that were removed during the harvest were recorded. The volume of removed trees was calculated from preharvest measurements and were totaled for each plot. Plots were then averaged across stands to give stand-level yield.

Finally, growth plus yield (G + Y) was calculated by adding the yield occurring from the two harvests to the net growth that occurred during the study period. Yield for the control stands was always zero since there were no harvests. G + Y was analyzed with the objective of detecting any differences in timber productivity between treatments. Analysis of covariance (ANCOVA) was used, with G + Y as the response variable, treatment as the predictor variable, and initial stocking level (the amount of standing volume at the beginning of the study period) as a covariable.

Initial stocking level was included as a covariable to account for any differences in productivity during the study period that were related to different initial volume density. Although there was no significant difference between treatments in terms of initial stocking level, it was included in the analysis since productivity is typically strongly associated with stocking (O'Curtis et al. 1997). Treatment effects were judged as significant at $P < 0.05$. Post hoc comparisons between pairs of treatments were made with Tukey's HSD tests (Zar 1999). Analyses were done using JMP 9.0 statistical software (SAS, Cary, NC).

Measuring species composition

I assessed change in species composition by measuring change in relative species abundance. This was defined as the change in relative basal area of trees > 10 inches DBH for a given species from the beginning of the study period to the end of the study period. For example, if a stand's total basal area had a relative proportion of 0.50 represented by Douglas fir prior to harvests and then 0.40 following the harvests, the change in relative basal area was –0.10. An overall change in relative basal area for each of the treatments was tested with ANOVA. Each harvest method was tested separately, with species as the independent variable and change in relative species basal area as the dependent variable. This served to evaluate whether there was an overall change in species composition for any of the treatments.

A post hoc evaluation of the degree to which individual species had changed was made for those treatments that were significant. This was done using a conservative approach: Individual species were judged to have changed significantly if the confidence interval of the amount of change did not overlap with zero (Ford 2007).

Productivity decline, species change

The treatments had a significant effect on G + Y for both merchantable volume ($P = 0.02$) and total stem volume ($P = 0.02$).

In the control stands, although yield was zero, productivity was similar to or greater than in stands harvested by thinning from below or single tree selection. Even though stocking was quite high (mean basal area > 300 square feet per acre), volume productivity was still high, as the stand continued to grow positively in standing volume over time.

Timber productivity was significantly reduced in the stands that were harvested by large-tree removal. Average merchantable volume in those stands was 0.66 thousand board feet per acre per year and 1.38 thousand board feet per acre per year for all the other stands combined (fig. 1A). Stem volume was 108 cubic feet per acre per year in stands harvested by large-tree removal and 214 cubic feet per acre per

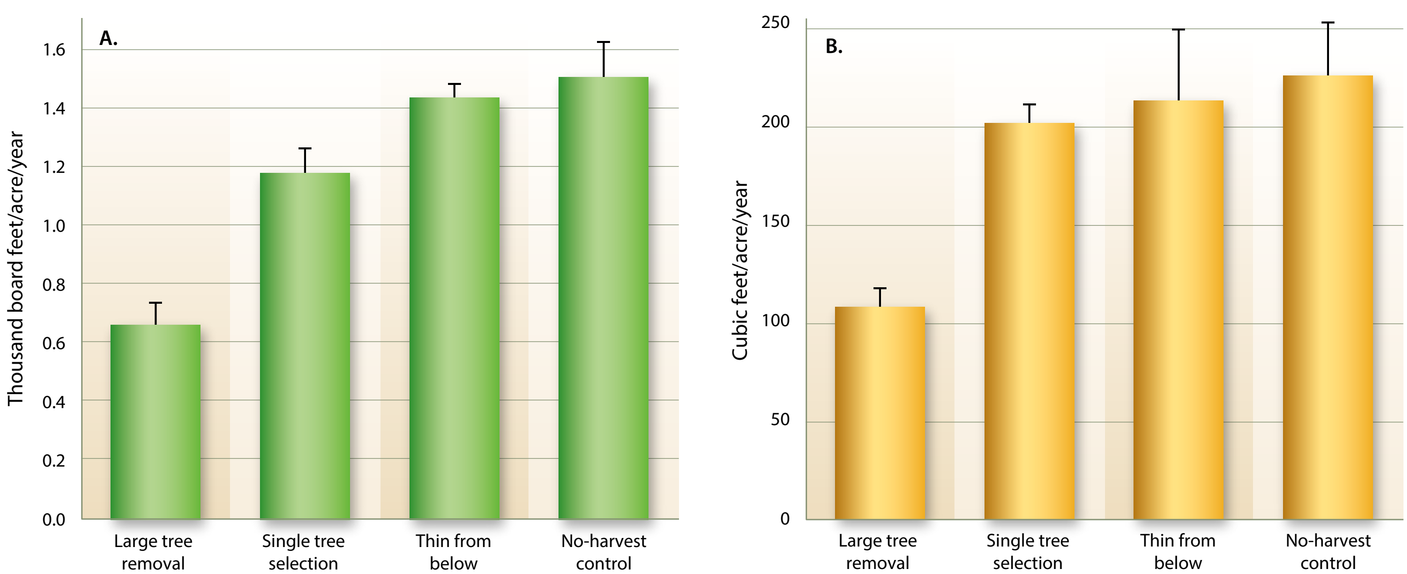


Fig. 1. Means and standard errors of growth + yield (G + Y), expressed in merchantable board feet (A) and total stem volume (B), among four treatments after two harvests at Blodgett Forest Research Station, CA.

year for all the other stands combined (fig. 1B). Merchantable timber productivity was also lower in large-tree removal stands with pairwise comparisons to all other treatments. Stem volume in large-tree removal stands was lower than in the stands that were harvested by single tree selection, but there were no other differences detected between pairs of treatments. Initial stocking level was not a significant influence on volume productivity. However, for merchantable volume it was suggestive ($P = 0.10$) that productivity in general increased with initial stocking, as would be expected.

Large-tree removal led to a notable change in canopy species composition and was the only treatment that led to a detectable change in overall species composition (fig. 2). Notably, black oak and especially white fir increased in relative basal area in stands harvested by large-tree removal. This increase was countered by a relative decrease in ponderosa pine. Other minor changes occurred but were not significant. Species composition of the no-harvest controls was relatively unchanged over the study period (table 1).

Long-term losses

Preferentially removing only the largest trees in forests can be an effective way to increase short-term profit, but the long-term effects measured in this study were decidedly negative: Timber productivity was cut in half, and white fir increased while ponderosa pine decreased. If forest management objectives include maintaining a high productivity and a canopy species composition that is similar to the time before fire suppression, then large-tree removal as practiced in this study deserves the pejorative name *high-grading*.

The reason for the change in species composition in these stands is ostensibly the outcome of the marking priority placed on large trees. Ponderosa pine and Douglas fir, both relatively fast growing, decreased in the canopy because they were the largest species at the time of harvest. The resulting increase in white fir is misaligned with the conventional objective of preferring a species composition closely associated with pre-fire

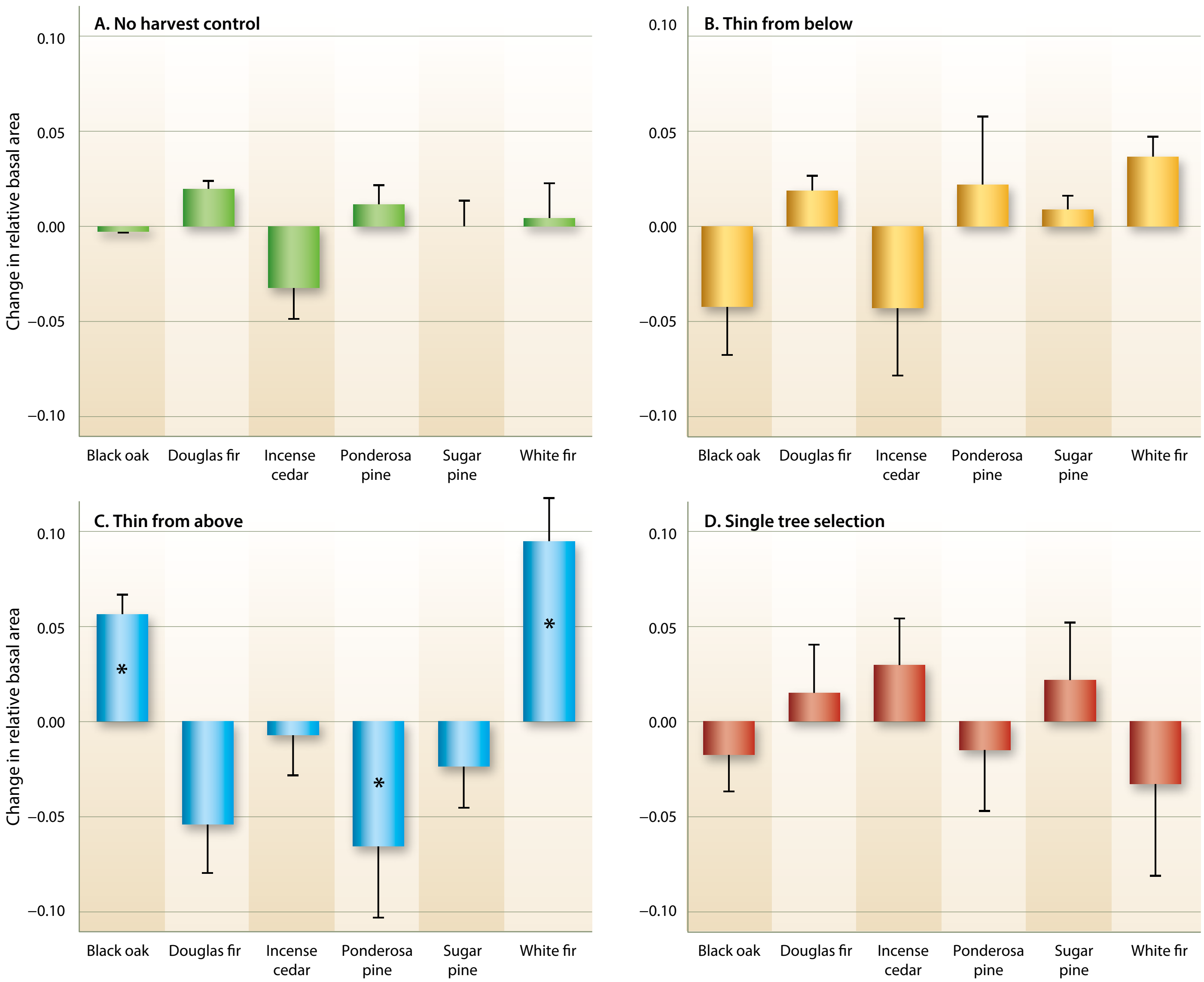


Fig. 2. Change in relative species composition in four treatments after two harvests at Blodgett Forest Research Station, CA. Large-tree removal was the only treatment with a detectable shift in species composition. Bars are means with standard error whiskers. Asterisks denote those species where the 95% confidence interval of the mean change did not overlap with zero.

suppression conditions. The widespread increase in white fir across intact Sierra Nevada forests (e.g., Ansley and Battles 1998) has been exacerbated by large-tree removal. It has come at the cost of ponderosa pine, which was by most accounts extremely more common prior to fire suppression (e.g., Hagmann et al. 2013). The other methods studied were arguably only slightly better in terms of species composition, as they also did not actively recruit ponderosa pine in the canopy.

The reason for the decline in timber productivity is less clear. One likely contributing factor is genetic bottlenecking. The second-growth stands used in the study are from a single cohort that derives from railroad logging disturbances approximately 100 years ago. Larger trees in second-growth forests such as these are often no older than their smaller neighbors. To the extent that genetic influences caused these trees to be larger, their removal would result in a proportionate dysgenic selection. This potential negative genetic effect of large-tree removal has long been recognized (Daniel et al. 1979) but seldom tested. Hawley et al. (2005) noted an increase in rare allele frequency following large-tree removal but also associated genetic factors with a loss of productivity in Northern hardwood stands.

TABLE 1. Relative basal areas (percentages) by species among different harvest methods before and after two harvest entries at Blodgett Forest Research Station, between 1980 and 2006

Treatment	Black oak		Douglas fir		Incense cedar		Ponderosa pine		Sugar pine		White fir	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
	basal area (%)											
Large-tree removal	13	18	19	14	35	35	15	8	3	0.1	14	23
Single tree selection	8	6	20	22	21	24	13	12	10	12	28	24
Thinning from below	10	6	6	8	28	24	35	37	1	2	19	23
Control: no harvest	4	4	16	18	27	24	15	16	9	9	27	28

The other likely contributing factor is in the difference in growth capacity between large and small trees. Large trees can be exceptional in their capacity to produce stem volume, both in intact forests (Stephenson et al. 2014) and following removal of competing vegetation (York et al. 2010). However, relatively high stem growth efficiency has also been observed in midstory trees in mixed-conifer forests (Gersonde and O'Hara 2005), causing uncertainty that growth efficiency was a primary contributing factor to the decline in productivity in the large-tree removal stands in the study.

Lastly, it may be that the large trees removed had, by chance, exclusive access locations, with high levels of underground resources. These sweet spots would seemingly be only a short-term contributor, however, as neighboring trees would eventually occupy much of the high-value growing space made available by the vacancy of the large trees.

It is likely a combination of factors that caused the productivity decline. The many factors that make a tree grow faster or slower prior to a harvest — genes, microsite, neighborhood effects and luck — continue to influence growth of trees remaining after a harvest.

Landowner options

To restore lost productivity and species composition in forests that have been harvested by large-tree removal, landowners have several options. While thinning from below may intuitively seem to be the countermeasure to large-tree removal, it would not address the impacts of genetic bottlenecking. Nor would it address the shift toward white fir, unless it was an

Clearcut

This method, where all trees are removed and the site planted, is more common on industrial lands. Nonindustrial landowners may alternatively choose group selection, where openings are smaller.

Will Suckow

intermediate step toward regenerating ponderosa pine in the future. Clearcutting and planting would be a way to start over, but nonindustrial landowners tend to avoid this, either because of their aesthetic objectives or because the permit options available to them (nonindustrial timber management plans and working forest management plans) do not allow even-aged methods.

A group selection harvest method that creates smaller openings of about an acre in size that are then planted can be a viable option (York et al. 2004), especially if fast-growing trees of native species, including ponderosa pine, are planted in the openings and are managed by thinning and control of other vegetation. Harvest by single tree selection, although more marginal in terms of ponderosa pine regeneration, may also work if designed and implemented carefully (York et al. 2011). CA

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Group selection

Creating small openings of about 1 acre in size and planting with native conifers can be an option for restoring high-graded forests on nonindustrial lands. This image shows an 18-year-old, ¼ acre patch in the mid-ground and a 4-year-old, ½ acre patch in the foreground.

Will Suckow

Post-fire vegetation dynamics of a sagebrush steppe community change significantly over time

by Sara K. Hanna *and* Kenneth O. Fulgham

Sagebrush steppe ecosystems of the Intermountain West have experienced a decline over the past 150 years due to changing fire regimes, invasive species and conifer encroachment. Prescribed fire is a common and cost-effective tool used in sagebrush restoration and fuels management. We examined the post-fire succession of a sagebrush steppe community over a nearly 30-year period at two study sites in northeastern California. The long-term nature of this study was particularly significant, as invasive annual grasses dominated the plant community in the years immediately following fire, but native perennial grasses and shrubs successfully out-competed them in the long term. Shrubs were slow to recover but had returned to pre-fire levels by the end of the study period. There was also notable increase in western juniper throughout the study sites, particularly in areas that had not been burned. Our results indicate that mean fire return intervals of 50 years or less would help reduce western juniper encroachment and preserve sagebrush habitat, especially for potentially threatened species such as the sage grouse.

The sagebrush steppe ecosystem, extending across hundreds of millions of acres throughout the Intermountain Region of the West (the area between the Cascade and Sierra Nevada Mountains to the west and the Rocky Mountains to the east), provides important wildlife habitat as well as economic, recreational and agricultural benefits. Sagebrush steppe habitat has declined in area, continuity and quality over the past century due to overgrazing, spread of invasive species and alterations to natural fire regimes. Human activities, including urban expansion, agriculture, and energy and mining operations, have further fragmented the sagebrush steppe landscape, which has led to loss of habitat for wildlife and a decrease in plant biodiversity and the productivity of the landscape (Anderson and Inouye 2001; Meinke et al. 2009; Miller and Rose 1999; Nelle et al. 2000).

One of the most common tools to restore sagebrush ecosystems is fire (Brown and Smith 2000); prescribed burning encourages biodiversity and the health of ecosystems. In the absence of fire, sagebrush stands become dense and conifers increase, reducing the perennial grass and forb components that constitute an important part of the sagebrush steppe landscape. This causes permanent shifts in the vegetation structure and composition. Fire suppression is a contributing factor in the conifer encroachment into the sagebrush steppe; expanding western juniper (*Juniperus occidentalis*) ranges have been observed throughout the West (Miller et al. 2005). In general, prescribed fire increases the biomass production of all herbaceous (non-woody) species and reduces woody species cover and the risk of conifer encroachment into the sagebrush rangelands.

One of the greatest concerns about using prescribed burning is the risk of an invasion of exotic species. The most notable invasive species in the sagebrush steppe is cheatgrass (*Bromus tectorum*). A second concern is that sagebrush is slow to recover following fire and consequently available forage, nesting and brooding habitat for sage grouse (*Centrocercus urophasianus*) are negatively affected (Baker 2006; Meinke et al. 2009). Sage grouse require a minimum of 20% sagebrush cover for winter forage and nesting (Beck et al. 2009). The loss and fragmentation of suitable sagebrush habitat has caused sage grouse populations to decline

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A view of the Lacy study site looking north, Clear Lake Reservoir, May 2009.

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dramatically over the past 30 years (Nelle et al. 2000). For example, sage grouse populations have diminished from more than 40 active leks (breeding grounds) to 1 lek on the Clear Lake National Wildlife Refuge (USDA 2011).

The effect of fire on an ecosystem is dramatically influenced by local environmental factors, including site-specific conditions such as soil and topography, and by land use and management goals. The objective of this study was to produce quantitative data on the long-term vegetation changes (over nearly 30 years) following a prescribed burn in a sagebrush steppe community — the immediate post-fire plant communities are often vastly different from those observed decades later.

Study sites and sampling

The study sites are located in the Clear Lake Hills in Modoc County, California (fig. 1), part of the Doublehead Ranger District in the Modoc National Forest. The Clear Lake Hills are on the western edge of the national forest, approximately 15 miles (24 kilometers) southeast of Tulelake, and are bordered to the east by the Clear Lake National Wildlife Refuge. In the Clear Lake Hills, the vegetation is primarily mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*) with an understory of perennial grasses and forbs and scattered western juniper. The climate of the Clear Lake Hills is characteristic of a semi-arid cold desert, with cold winters and relatively warm, dry summers.

In the early 1980s, the U.S. Forest Service selected two sites within the Chandler and Lacy pastures (areas leased to a grazer by the U.S. Forest Service) for prescribed fires. The sites were identified as the Chandler burn and the Lacy burn and are separated by a distance of 2.5 miles (4 kilometers) (fig. 1). At the Chandler site, in the late summer of 1980, the U.S. Forest Service conducted a prescribed burn of approximately 700 acres (2.8 square kilometers). The site was divided into four sampling areas — Northeast, Southeast, Center and Northwest — to account for the undulating topography and varying soil textures (fig. 2). Pre-fire sampling was not completed by the fire date. At the Lacy site, in early August of the following year, approximately 300 acres (1.2 square kilometers) were burned. The Lacy site had a relatively homogenous landscape, so was not divided into smaller sampling areas, and pre-fire sampling was conducted before the fire date.

The sites had a history of seasonal grazing but were not grazed by any livestock for two growing seasons prior to the burns. Following the burns, they had no cattle grazing for at least 2 years, but there was early-spring grazing by sheep to help control competition from annual grasses, namely, cheatgrass. After 2 years, the sites were grazed every year, in early spring by sheep, in summer by cattle or by cattle and sheep (Brad Reed, U.S. Forest Service Resource Officer (retired), personal communication).

Vegetation sampling. Field data collection consisted of measuring vegetative cover and herbaceous biomass production at each study site. Vegetative cover was measured using the line-intercept method, which is commonly used to measure vegetative cover and composition on rangelands (Canfield 1941). Permanent transects 100 feet (30.48 meters) long were randomly located at both sites prior to the fires, and measurements were taken along those transects in each sampling year.

Herbaceous biomass production was measured for each plant species using six production plots 1 meter square (10.76 square feet), randomly located along each transect. Within each plot, all aboveground biomass was clipped, bagged and labeled. At the Lacy site, there were 10 transects, and a total of 60 production plots sampled each year. At the Chandler site, there were five transects in each of the four sampling areas, for a total of 20 transects and 120 production plots sampled each year. For analysis purposes, the species-level data collected for both cover and productivity were summarized into the following five morphological groups:

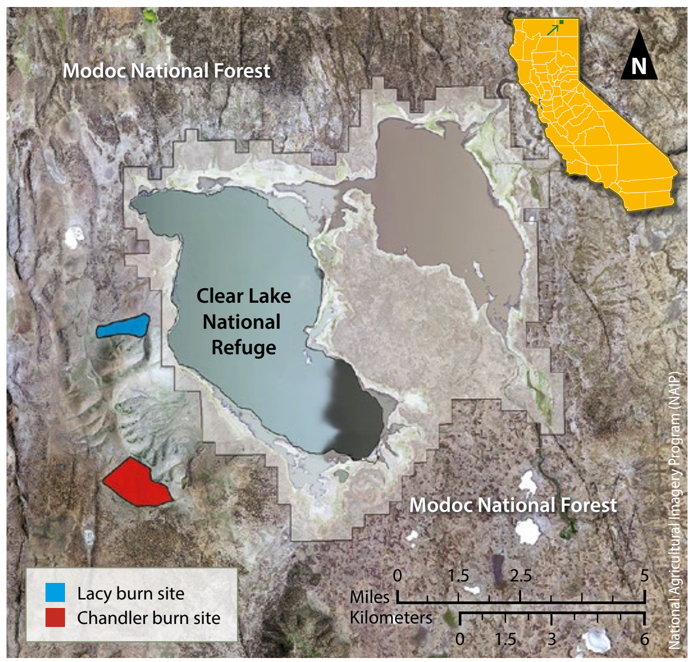

Fig. 1. Location of the study sites in the Clear Lake Hills, Modoc County, California.

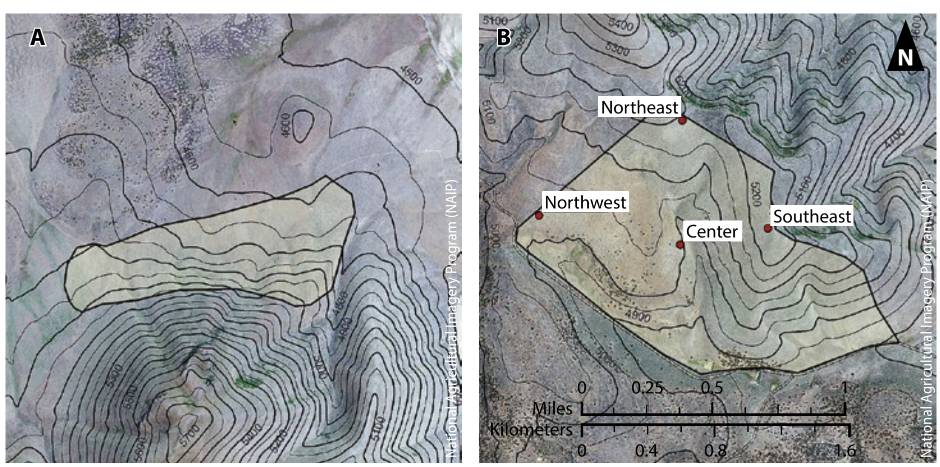

Fig 2. Topography of the Lacy site (A), and the Chandler site with the four sampling areas (B).

Fire is one of the most common tools to restore sagebrush ecosystems. In the absence of fire, sagebrush stands become dense and conifers increase, reducing the perennial grass and forb components that are an important part of the sagebrush ecosystem. *Above*, prescribed fire at the Lacy site, summer 1981.

annual grasses, perennial grasses, annual forbs, perennial forbs, and shrubs.

Pre-fire data was collected at the Lacy site prior to the prescribed burn, but not at the Chandler site, because the U.S. Forest Service conducted that burn early. Post-fire data was collected during the 3 years immediately following the fires, and then 10 years after the fires and 20 years after the fires. The final sampling was conducted in 2009, representing 28 post-fire growing seasons at the Lacy site and 29 post-fire growing seasons at the Chandler site. Statistical analysis consisted of multivariate analysis of variance (MANOVA) and post-hoc univariate analysis of variance (ANOVA) tests. The Bonferroni correction factor was applied to correct for multiple comparisons.

In fall 2011, additional shrub cover sampling was conducted in three unburned areas adjacent to the Chandler Northwest, Northeast and Southeast sampling areas. There was no comparable unburned area for the Center sampling area.

Western juniper. In 2010, a random sample (n = 6) of juvenile (< 3 feet tall) western junipers at the Chandler Center sampling area was selected for aging. Selected trees were cut down, and cross sections were removed from the base of each tree. Ages were determined using standard tree ring dating techniques. To better estimate the changes in western juniper canopy cover, aerial photographs of the study sites were obtained — black-and-white aerial images from 1975 from the United States Geological Survey (USGS) and color aerial images from 2012 from the National Agriculture Imagery Program (NAIP). Canopy area was estimated using ERDAS Imagine software to conduct supervised classification of the images.

Post-fire vegetation dynamics

Herbaceous cover and productivity. The long-term post-fire vegetation dynamics at the Lacy and Chandler sites were comparable over the nearly 30-year sampling period; however, there were significant differences among the four Chandler sampling areas in cover and productivity (P < 0.001) (data not shown). This confirmed that site conditions such as soil, topography and pre-fire species composition all factor into the recovery of the post-fire plant community.

A comparison of the pre-fire and the 28-year post-fire vegetative cover and production at the Lacy site revealed significant differences in both vegetative cover and herbaceous productivity (P < 0.001); the differences were primarily due to a reduction in annual grasses (P < 0.001) and an increase in perennial forb cover and productivity (P < 0.001) (tables 1 and 2). The secondary succession following the burns was as anticipated, with the initial plant community consisting primarily of herbaceous species. The earliest vegetative recovery was observed in the understory species. Fire effectively removed the woody shrub component of the plant community and shifted the plant community to an herbaceous grass-dominated community at both sites (figs. 3 and 4).

Herbaceous biomass production increased dramatically in the growing seasons following the prescribed burns. The increase was particularly apparent in annual grasses, whose life history pattern

TABLE 1. Mean and standard error (SE) herbaceous biomass production, in grams per square meter, for the Lacy and Chandler burn sites

		Annual grasses		Perennial grasses		Annual forbs		Perennial forbs	
	Year	Mean	SE	Mean	SE	Mean	SE	Mean	SE
		grams/square meter							
Lacy site	1981 (Pre-fire)	4.93	0.82	10.26	1.49	0.00	0.00	0.22	0.20
	1982	27.03	5.46	9.89	1.85	2.39	1.04	0.90	0.64
	1983	134.00	17.64	14.21	4.92	1.03	1.41	3.43	3.13
	1984	49.11	7.81	12.71	3.75	0.13	0.16	1.21	1.43
	1991	11.57	3.47	45.79	4.22	0.47	0.17	6.37	5.80
	2001	6.50	3.01	35.12	5.95	0.18	0.10	9.50	5.57
	2009	0.18	0.17	12.36	2.07	0.12	0.10	9.26	2.86
Chandler site	1981	6.58	1.49	23.55	1.70	9.48	1.11	4.92	1.33
	1982	42.61	4.96	57.72	4.24	2.11	0.57	6.53	1.15
	1983	24.95	3.14	61.60	3.60	2.90	0.42	10.78	1.69
	1990	11.85	1.69	80.20	4.91	1.90	0.61	8.12	1.23
	2000	5.44	1.55	47.91	3.63	12.64	2.41	11.56	1.76
	2009	0.53	0.11	23.83	1.27	1.48	0.25	9.79	1.07

facilitates rapid growth and seed production on post-disturbance sites (Barbour 1999). Annual grasses, primarily cheatgrass, expanded rapidly following the fires, at both sites. Annual grass cover and productivity increased in the immediate post-fire years but were much greater at the Lacy site than the Chandler site (tables 1 and 2). At the Lacy site, annual grass cover was more than 10 times that of pre-fire levels. At the Chandler site, the majority of annual grasses observed was at the Northwest sampling area (data not shown).

The fact that the Northwest area was the only Chandler area to have a persistent, significant annual grass presence suggests that the prevalence might be explained by local environmental and topographic characteristics. This area was the closest to the road and was immediately adjacent to a gate; the area had been used as a livestock staging area, increasing the risk of soil disturbance and introduction of invasive species. There was also less perennial grass and forb cover in the Northwest area.

Numerous studies, as cited by Knapp (1996), have shown that cheatgrass frequently dominates plant communities following soil disturbances, like fire. By the 10th growing season of our study, annual grasses (cheatgrass) were surpassed by perennial grasses at both sites, though there was an anomalous increase in annual grass cover at both sites in the 20th post-fire growing season. After 28 growing seasons at the Lacy site, annual grass cover and productivity levels were significantly lower than the pre-fire levels ($P < 0.001$) (tables 1 and 2).

Native perennial grass cover and productivity generally increased at both sites in the post-fire years but at a slower rate than annual grass cover and productivity. Within two growing seasons following the Lacy burn, perennial grass productivity had surpassed pre-fire levels. It continued to increase at both sites, peaking 10 years after the fires. Perennial grass cover peaked 20 years after the fires. Perennial

TABLE 2. Mean and standard error (SE) percentage of vegetative cover in the Lacy and Chandler burn sites

		Annual grasses		Perennial grasses		Annual forbs		Perennial forbs		Shrubs	
	Year	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
		grams/square meter									
Lacy site	1981 (Pre-fire)	1.41	0.18	6.43	0.64	0.08	0.05	0.66	0.19	28.48	1.12
	1982	3.82	0.42	2.71	0.29	1.46	0.16	0.87	0.29	0.00	0.00
	1983	11.47	1.20	3.98	0.49	1.23	0.10	2.54	1.17	0.08	0.03
	1984	18.73	2.10	5.03	0.51	1.11	0.08	1.18	0.64	0.16	0.05
	1991	3.38	0.31	13.23	0.54	0.58	0.03	0.83	0.26	1.47	0.37
	2001	6.91	0.85	13.17	0.69	1.10	0.08	3.57	0.45	14.72	1.90
	2009	0.23	0.04	8.23	0.74	0.15	0.05	3.64	0.52	27.81	2.55
Chandler site	1981	0.81	0.43	6.17	1.33	2.21	1.75	2.90	1.00	0.02	0.05
	1982	6.74	3.04	9.31	0.22	0.77	1.94	2.99	1.55	0.08	0.14
	1983	5.95	2.33	11.43	0.74	2.42	3.85	6.70	2.27	0.55	0.58
	1990	4.61	1.92	16.36	1.08	2.30	1.39	4.22	1.51	3.83	2.24
	2000	6.18	4.02	18.68	1.44	2.27	1.46	5.50	3.69	12.42	5.09
	2009	0.61	0.35	11.73	0.51	1.05	1.44	4.29	1.89	19.76	4.97

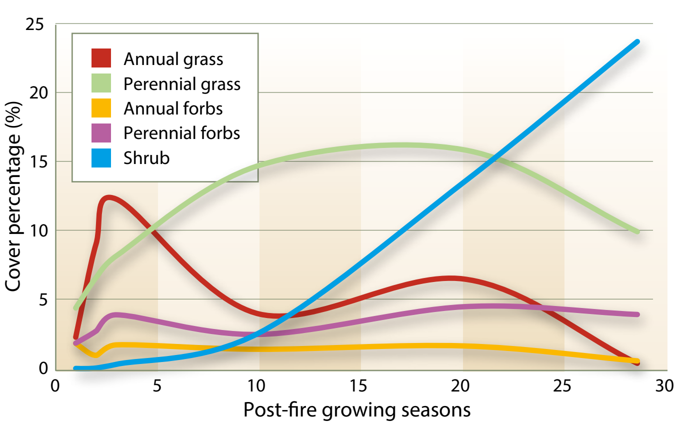

Fig. 3. Mean percentage of vegetative cover at the Lacy and Chandler sites over 28 growing seasons, by morphological group.

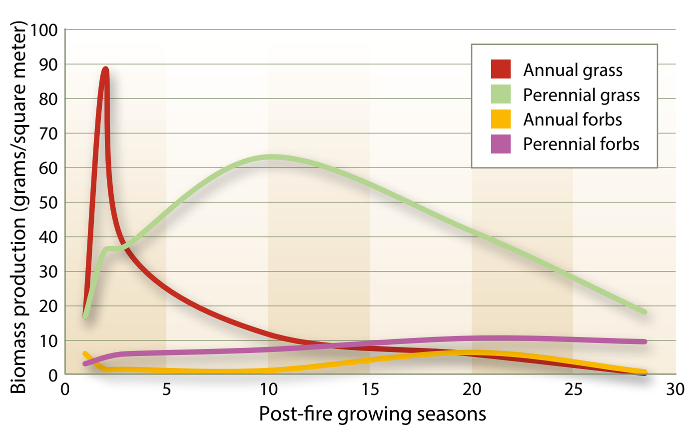

Fig. 4. Mean herbaceous biomass production, in grams per square meter, at the Lacy and Chandler sites.

grass biomass production increases rapidly due to the release of competitive pressure, while density and cover take longer to recover (Bunting 1985).

In 2009, perennial grass cover and productivity at the Lacy site were still significantly greater than the pre-fire levels there (P = 0.05 and P = 0.04). The recovery and health of the perennial grasses support existing research indicating that many native perennial grasses in mountain sagebrush communities respond positively to fire, with increasing cover and productivity (Ellsworth and Kauffman 2010; Wright 1985). Our data confirms that the native perennial grasses in these plant communities are resilient and capable of withstanding the competitive pressures of cheatgrass.

Annual and perennial forb productivity and vegetative cover fluctuated throughout the sampling period, especially at the Chandler site (data not shown). As observed with the annual grasses, annual forbs are well adapted to establish following disturbances and can quickly dominate an area. Perennial forb cover and productivity generally increased at both sites following the fires, suggesting that fire is not detrimental to perennial forbs. Perennial forbs generally fared well in the post-fire plant community, when shrub-dominated competition was removed by the fire. Most of the perennial forbs of the area have belowground growing tissues that allow protection from fire and quick resprouting (Sugihara et al. 2006).

Sagebrush and shrubs. Fire effectively eliminated all shrub cover, and recovery was slow, with only minimal shrub cover observed until 10 to 20 growing seasons after the fire (fig. 5). Early shrub cover was mostly rabbitbrush species, which are avid sprouters and capable of rapid recovery following fire (Sugihara et al. 2006). Mountain big sagebrush re-establishment, however, is entirely dependent on the germination of unburned seeds (Sugihara et al. 2006).

By 2009, sagebrush cover was equivalent to the pre-fire level at the Lacy site, about 30% (P = 0.54). A comparison in that year of the Chandler (burned) site with the three Chandler control (unburned) areas also confirmed that shrub cover after nearly 30 years was comparable. Shrub recovery rates did not differ significantly among the four Chandler sampling areas or between the Lacy and Chandler sites, which indicates that shrub recovery rates were relatively stable across the study area.

Western juniper. The Intermountain West has seen a dramatic increase in the density and spatial distribution of pinyon and juniper woodlands in the past century. An analysis of the aerial photographs from 1975 (pre-fire) and 2012 confirmed this occurrence (figs. 6 and 7). In pre-fire 1975, the Chandler pasture boundaries (7,000 acres) had approximately 184 acres classified as western juniper. By 2012, the area classified as western juniper had nearly tripled, to

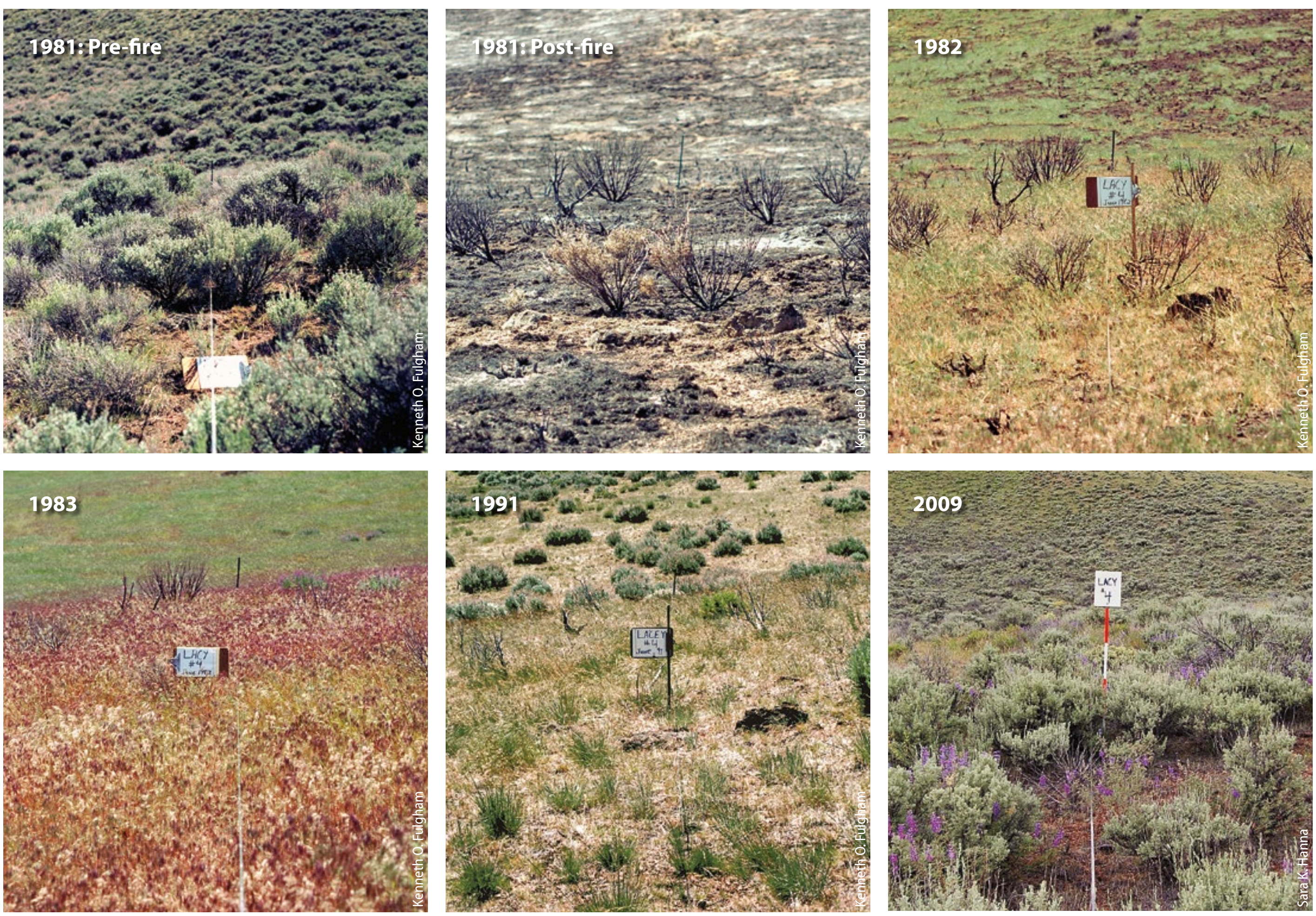

Fig. 5. Vegetation at transect 4 at the Lacy site throughout the monitoring period, from before the fire in 1981 to 2009, 28 years later.

529 acres, outside the burn. Within the Chandler burn site, there was an increase in western juniper but to a much lesser degree, with 2.5 acres classified as western juniper in 1975 and 4.1 acres in 2012. Results were similar in the Lacy pasture (3,200 acres), with western juniper cover doubling between 1975 and 2012 (from 7.8 acres to 16.3 acres). Again within the burn site, there was minimal increase in western juniper, from 0.8 acre in 1975 to 0.9 acre in 2012.

Within the burn sites, western juniper growth was most apparent on the eastern slope in the Chandler Center sampling area. While several of the old-growth junipers survived the fire in that area, many others died and eventually fell over. The western junipers sampled in 2011 for aging were determined to be from a cohort of 13 to 20 years old (mean 15.5 years). Western junipers do not re-sprout; they regenerate primarily from seed (Miller et al. 2005), and most of the western junipers observed after the fire had established post-fire from seedbanks. Young western juniper trees (less than 50 years old) are not fire tolerant and are easily killed by fire (Miller and Rose 1999). Our research confirms previous study results by Miller and Rose (1999) and Burkhart and Tisdale (1976) that the mean fire return intervals would need to be 50 years or less to reduce western juniper woodland encroachment into mountain big sagebrush communities.

Long-term perspectives

The long-term nature of this study was particularly important, as the plant communities immediately post-fire, 10 years later and nearly 30 years later each were dramatically different. Invasive annual grasses dominated the plant community in the years immediately following the fires, but native perennial grasses overtook the annual grasses in the long term. Perennial grass and forb recovery was robust at both burn sites.

Estimations of sagebrush recovery have varied widely (25 to 100 years), depending on the sagebrush subspecies and environmental conditions (Sugihara et al. 2006). This study confirms that while sagebrush is slow to re-establish, it can recover to pre-fire levels in approximately 30 years, especially at mesic, productive sites like the Clear Lake Hills. The rate of sagebrush recovery is of particular concern due to the serious decline of sage grouse populations. The slow rate of sagebrush recovery suggests that small-scale mosaic burns, in which relatively small areas of land are burned at varying intervals to create both burned and unburned patches in the landscape, are most appropriate to preserve a variety of available habitat and forage for sage grouse: The unburned areas would maintain adequate sagebrush cover for nesting, and the burned areas would increase the availability of herbaceous species utilized by the sage grouse and reduce the rate of conifer encroachment.

A significant expansion of western juniper was observed in Lacy and Chandler pastures throughout the monitoring period, resulting in decreasing productivity and diversity of understory vegetation.

Invasive annual grasses dominated the plant community in the years immediately following the fires, but native perennial grasses overtook the annual grasses in the long term.

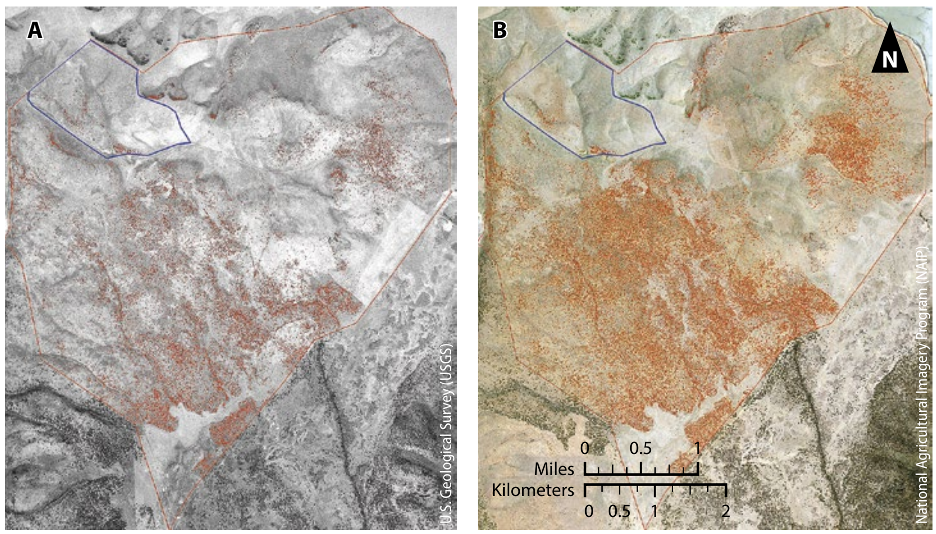

Fig. 6. Aerial photographs from 1975 (A) and 2012 (B) of the Chandler pasture, showing areas classified as western juniper in red. The prescribed fire site is shown in blue.

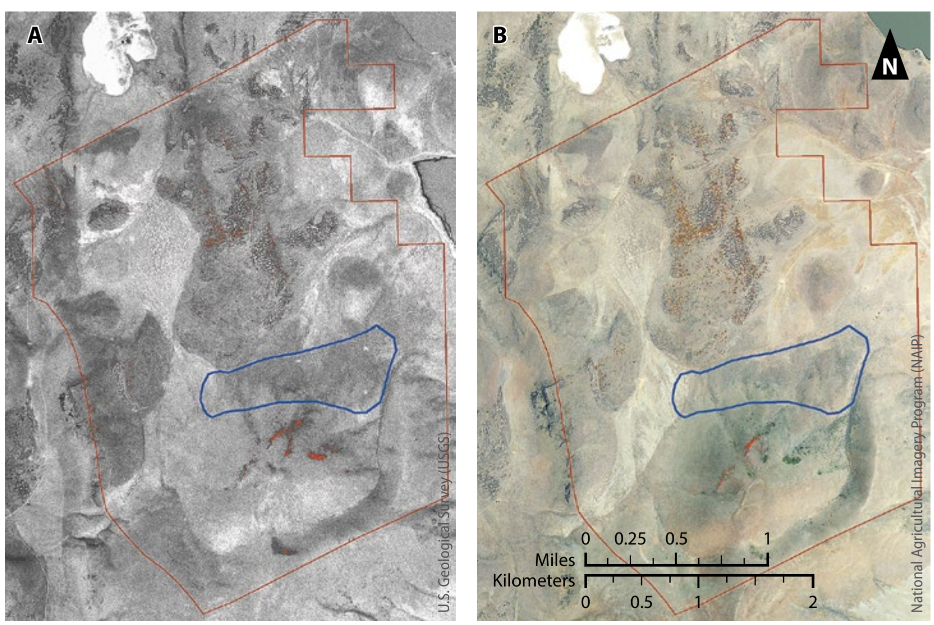

Fig. 7. Aerial photographs from 1975 (A) and 2012 (B) of the Lacy pasture, showing areas classified as western juniper in red. The prescribed fire site is shown in blue.

In the burn sites, western juniper cover increased, but significantly less so than in the unburned areas. This indicates that a 30- to 40-year fire return interval might reduce western juniper encroachment and maintain a productive and diverse ecosystem.

In terms of the impact of grazing on the post-fire vegetation dynamics, the early sheep grazing may have contributed to the reduction in annual grasses seen at both sites and reduced their persistence and density. The impact of early sheep grazing on the post-fire succession is difficult to quantify without a control treatment. Grazing before a fire can reduce the accumulation of dead plant material around the crowns of grasses, reducing fire residence time and plant mortality (Wright and Klemmedson 1965). Grazing has also been shown to increase the resilience of plant communities following disturbance (Bates et al. 2009). Recent studies have shown that moderate, properly administrated grazing does not hinder the post-fire recovery of herbaceous plants in sagebrush steppe (Bates et al. 2009).

While the post-fire successional patterns were similar at the two sites, there were differences in their trajectories. Shrub recovery rates were stable across the sites, but the recovery rates of herbaceous species were more varied. The spatial complexity of sagebrush steppe communities following fire was especially apparent at the Chandler site, where the four sampling areas varied significantly in their post-fire vegetative cover and productivity. This confirms that successional patterns are often very site-specific in sagebrush steppe communities (Bunting et al. 1987; Miller and Rose 1999). Site conditions, including differences in topography and soil characteristics, influence the pre-fire plant communities and therefore the post-fire succession. In mesic, relatively healthy mountain sagebrush communities, native perennial grasses and forbs can respond positively to fire and outcompete invasive annual species. Sites that are degraded and have reduced native grass and forb populations prior to fire may have slower post-fire recovery times and be at the greatest risk for annual grass invasion. While our study confirms a degree of variability in the post-fire vegetation dynamics, the rates of sagebrush recovery were consistent across the sites at approximately 30 years. Therefore, agency land managers, scientists and others will find this information useful in forecasting post-fire vegetation re-establishment and recovery, and in determining whether or not prescribed fire is suitable for a given sagebrush community. This is particularly relevant for management of rare, threatened and endangered species. CA

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A male sage grouse (*Centrocercus urophasianus*) struts for a female at a lek, an open area where males perform courtship displays. At Clear Lake National Wildlife Refuge, the number of leks has declined over the past 30 years from 40 active leks to 1 lek.

Jeanne Stafford/U.S. Fish and Wildlife Service

UC plays a crucial facilitating role in the Sierra Nevada Adaptive Management Project

by Adriana Sulak, Lynn Huntsinger *and* Susan D. Kocher

The 2004 Sierra Nevada Forest Plan Amendment adopted by the U.S. Forest Service called for using adaptive management — management through deliberate experimentation — to carry out treatments to improve forest health and reduce fire severity. The Sierra Nevada Adaptive Management Project (SNAMP), begun in 2005 and ending this year, has developed, implemented and evaluated participatory adaptive management processes in two national forests for applying fuels management treatments based on strategically placed patterns of tree thinning. SNAMP participants include federal and state agencies, the University of California and many members of the public. UC Cooperative Extension staff members have played an important role in facilitating the participation of public stakeholders. In 2010, a survey showed that stakeholders valued the learning opportunities of the project, especially appreciating the open discussions, public input and face-to-face contact with scientists. Despite the institutional limits to sharing decision making, an environment conducive to the social learning characteristic of collaborative adaptive management projects was created. The SNAMP process may lead to long-term relationships and knowledgeable stakeholders who can support the Forest Service's use of the project findings after UC's role ends.

Debate over how best to prevent wildfires has continued for decades while the costs of wildfire protection and recovery have increased rapidly, with California spending $599 million in 2013 for firefighting alone — up by more than $100 million from 2012 (NBC 2014). Federal agencies spent a similar amount in the state in 2013, with California accounting for about half of all federal spending on fire suppression.

The U.S. Forest Service manages over 20 million acres in California, much of it adjacent to homes and communities. Fire hazard management on these public lands, especially if it involves removing trees, is often argued to be essentially at a standstill (Broussard and Whitaker 2009). Large trees are especially appreciated by the public for their beauty and as wildlife habitat associated with old-growth forests, home to, for example, the endangered California spotted owl and rare Pacific fisher. Controversy stemming from uncertainty about the environmental consequences of fuels treatments such as mechanical tree thinning is increasing the already substantial costs of those treatments and limiting their implementation. The gridlock led the U.S. Forest Service to specify the use of an adaptive management approach in its 2004 Sierra Nevada Forest Plan Amendment (USFS 2004).

The 2004 amendment intensified the debate about fire hazard management and environmental priorities by mandating a management strategy "with the primary objective of protecting communities and modifying landscape-scale fire behavior to reduce the size and severity of wildfires," and allowing the removal of trees larger than specified by the 2001 Sierra Nevada Forest Plan Amendment (USFS 2004). Widespread concerns arose among the public and natural resource agencies about how a program that makes fire hazard reduction a top priority might impact the forest ecosystem. In response, in 2005, the Forest Service, the U.S. Fish and Wildlife Service and the California Resources Agency signed a memorandum of understanding calling on the University of California (UC)

Sheila Whitmore

SNAMP researchers analyzed the effects of vegetation management treatments in the Sierra Nevada on forest health, fire behavior, water and wildlife such as the endangered California spotted owl.

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to act as a "neutral third party" to assist in developing a participatory adaptive management process for carrying out the forest management practices called for in the amendment. The result was the Sierra Nevada Adaptive Management Project (SNAMP 2005).

UC provided third-party science and outreach services within SNAMP; UC Cooperative Extension (UCCE) expertise in facilitating stakeholder participation was a crucial part of the project. UC was chosen for the research and outreach role because of its perceived credibility with stakeholders on both sides of the Sierra forest management debate. Other factors were UCCE's extensive network of outreach professionals and its long history of working with stakeholders on collaborative projects. UC researchers included scientists from UC Berkeley, UC Merced and UCCE; they worked with researchers from the University of Wisconsin and the University of Minnesota, together known as the "science team."

The SNAMP cycle

Adaptive management, as first described by Holling (1978) and Walters (1986), is a systematic approach to learning about complex ecological systems through deliberate experimentation and improving management by learning from the results. It allows managers to act without complete information about a system (Morghan et al. 2006), and it has evolved to include an emphasis on public participation (Gregory et al. 2006; Stringer et al. 2006).

Within SNAMP, the Forest Service planned and carried out the management treatments, which required a regular National Environmental Policy Act (NEPA) public consultation process. Forest Service planning calls for vegetation management treatments (Finney 2001) designed to modify fire behavior across the landscape and reduce forest crowding. The goal was to treat approximately 20% to 30% of the landscape but reduce the fire risk on 100% of it by removing some trees and clearing beneath the trees in strategic areas. This reduces flammable material in the project area and therefore reduces the impact of a wildfire, should one occur there or nearby.

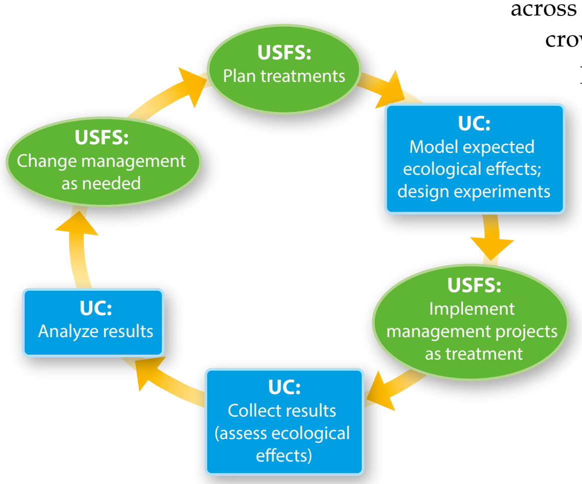

Fig. 1. The SNAMP cycle of planning and implementing management treatments, and learning from the results to change management direction. At each phase, scientists and the Forest Service report and interact with stakeholders through integration meetings, annual meetings and field trips facilitated by UCCE.

TABLE 1. SNAMP teams and their research objectives

Team	Research objectives
Public participation	Model, research and transfer outreach and public participation strategies, including use of an interactive website, strategic facilitation, collaborative adaptive management workshops and integration meetings.
Water	Treatment effects on streams and the forest water cycle.
Fire and forest ecological health	Treatment effects on fire behavior and tree morbidity and mortality. Model vegetation change after treatment, along with fire behavior modeling, to simulate long-term effects on wildfire spread and severity. Develop fire histories.
Spatial data	Map the forest before and after treatments and measure forest habitat characteristics across treated and untreated sites, including the use of Lidar technology.
California spotted owl (*Strix occidentalis occidentalis*)	Treatment effects on owl survival, occupancy and reproduction via a retrospective analysis that compares 20 years of annual vegetation changes with owl demographic rates in the northern study area.
Pacific fisher (*Martes pennanti*)	Treatment effects on fisher habitat quality. Correlation of environmental factors with population stability or change. Survival and behavior within four watersheds, including the SNAMP southern study area.

The science team designed and conducted research on treatment effects. The science team was comprised of smaller teams focused on the effects of treatments on California spotted owls, Pacific fishers, water, fire behavior and forest health, and teams focused on spatial analysis of the forest projects and on public participation (table 1). Each research team developed methods for evaluating the effects of the treatments for their area of research, informing the public about their choices and incorporating feedback when possible.

The science team reported the results of treatments back to the Forest Service and the public in order to improve future treatments in the next adaptive management cycle, and to help participants understand the effects of tree thinning on multiple resources (fig. 1). The science team's work plan stated that "adaptive management must be a participatory process that engages scientists, stakeholders, and managers in a long-term relationship grounded in shared learning about the ecosystem and society" (UCST 2007). Members of the science team signed a neutrality statement agreeing not to use SNAMP data for advocacy through the project's duration.

In conjunction with its Forest Service partners, the science team chose two study sites on the western slope of the Sierra: one in the southern Sierra, the Sugar Pine project, and the other in the northern Sierra, the Last Chance project (fig. 2). Each study site has control and treatment areas where pre- and post-treatment data were collected. Thinning treatments began in 2011 and were followed by treatments for clearing beneath the trees that included mastication (grinding, shredding or chipping) and underburning to manage fuel loads and vegetation. At this point, data collection is complete and the final report is being assembled.

The original work plan put together by UC and UCCE was peer reviewed by outside scientists, and the reviews were shared with the public. The research and outreach teams reported directly to the public, the memorandum of understanding signatory agencies and the Forest

Service about the design, methods and outcomes of their research into the effects of chosen management treatments. Research results are being published in peer-reviewed journals — briefs of each publication and a list of publications are available at the project website, snamp.cnr.berkeley.edu. Forest Service staff, from regional representatives and district managers to field technicians, attend, and frequently present, at SNAMP events.

To include the public, as stated in the science team's work plan, from research design to interpretation of results, an outreach strategy emphasizing inclusiveness and transparency was developed using UCCE's training and experience. UCCE has coordinated and facilitated all public, researcher and manager involvement in SNAMP, including integration meetings on specific research topics, field trips, lectures, annual meetings and presentations to local, state and regional groups and local high schools, and it manages an interactive website for sharing meeting information, notes, reports and responses to comments and questions (fig. 3). UCCE

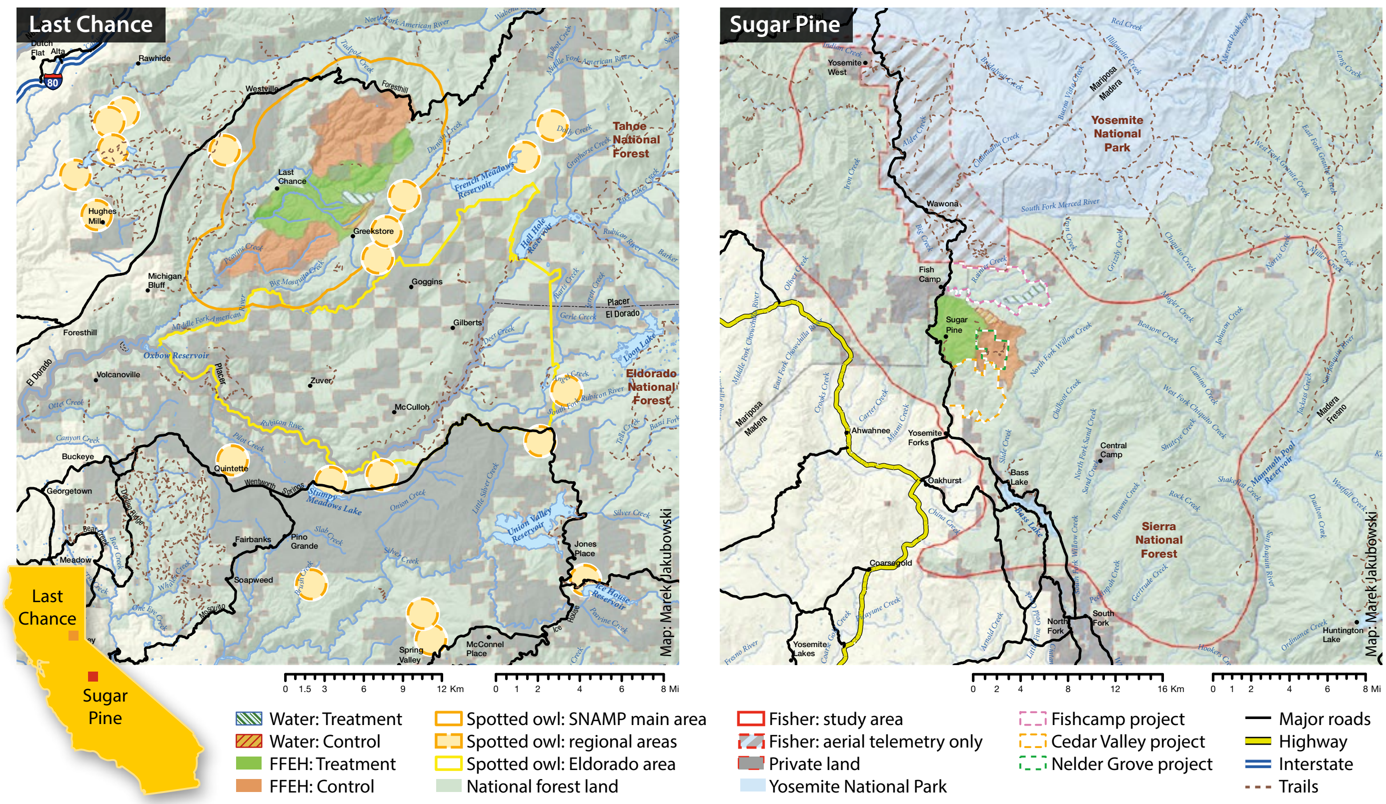

Fig. 2. SNAMP study areas. The northern site, Last Chance, is in the Tahoe National Forest; in this part of Placer County in the north-central Sierra Nevada, mixed-conifer forests include habitat for the California spotted owl. The southern site, Sugar Pine, is in the Sierra National Forest; on the western slope of the central Sierra Nevada, mostly in Madera County, this mixed-conifer forest provides habitat for the Pacific fisher and the California spotted owl.

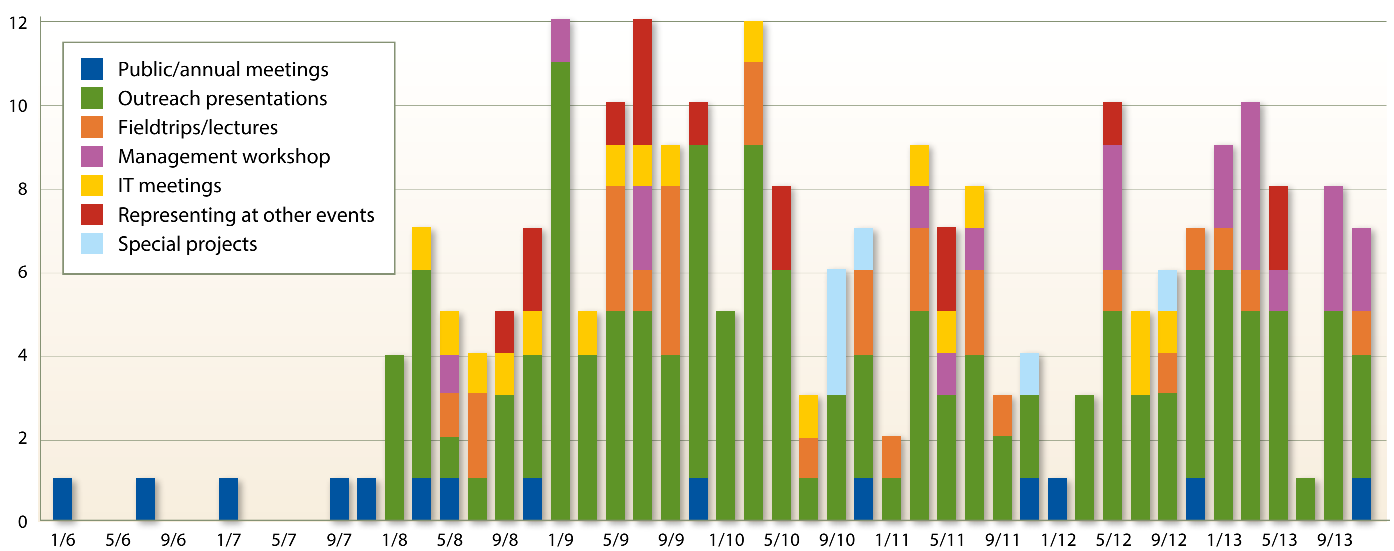

Fig. 3. UCCE facilitated 244 events from 2005 to 2013 to engage the public in SNAMP.

has also frequently represented SNAMP at board of supervisors meetings, local interest group member meetings and other venues; a member of the public participation team lives near each of the two project sites, helping to make local connections and conduct outreach.

Survey of stakeholders

One of the project goals was to test and model outreach methods, and to assess the value of the adaptive management model to stakeholders. Just as it is important to understand how thinning treatments affected the forest, it is also important to determine what worked and what did not work about the participatory adaptive management approach, to provide guidance for future projects. Such assessments are also a "best practice" for UCCE outreach programs to determine if outreach is reaching the target audience.

To find out who was participating in SNAMP, what their different perspectives were, and what they believed they were getting out of the process, a survey was undertaken in summer 2010. The 2010 survey investigated aspects of SNAMP that the literature emphasizes as important to adaptive management projects: enhancing learning, creating shared understanding, building social legitimacy for decision making and establishing relationships that support learning and adaptation in the long run (Arnold et al. 2012).

Email contacts on a list maintained by UCCE to promote SNAMP events and update stakeholders were invited to respond to the web-based survey. The contact list was comprised of individuals who wanted to be informed about SNAMP progress or who had attended SNAMP events. Of the 647 people on the list who were invited, after four prompts, 168 completed the survey, for a 26% response rate, which is similar to return rates for other email surveys (Sheehan 2001). Survey respondents are representative only of contacts interested enough to fill out the survey and inferential statistics are not applied. Survey questions were mostly multiple choice with the option for further comment; they were organized around the themes of who participates in SNAMP and how; what their perspectives are on forest health, adaptive management and the SNAMP process; and what they believe they are getting out of the project.

Around half [of survey respondents] agreed SNAMP was improving relationships and increasing trust.

Of the participants who responded to the survey, 62% were male and 67% lived in a forested area. The average age was 52, with the oldest 82 and the youngest 27. All respondents who reported an education level had graduated from high school and attended at least some college or trade school. A quarter had a bachelor's degree and 44% had completed a professional or graduate degree. A quarter of the respondents had not been to a SNAMP meeting but 80% of all respondents had visited the website or participated in a webinar. Of the respondents who had attended SNAMP events, most had been to four or fewer events (68%).

There were a large number of respondents who described themselves as "members of the general public" (fig. 4). Many of the others were associated with federal or state agencies or conservation groups. Respondents also included members of forest products groups and Native American tribe representatives. Around half of respondents were from the counties around the study sites. The other half came from cities and rural areas all across the state (fig. 5), a benefit of the extended reach of the website (Kelly et al. 2012).

What respondents said

The vast majority of respondents felt that participation in SNAMP was worth their time and meetings were well organized and facilitated (fig. 6). There was strong agreement that SNAMP facilitated learning and that discussions between participants and presenters were encouraged and conducted in an open and informal manner with enough face-to-face contact with scientists and managers. Most agreed that they felt part of the project and that they were listened to by researchers. Around half agreed SNAMP was improving relationships and increasing trust. The sentiment that the SNAMP process was building consensus, though

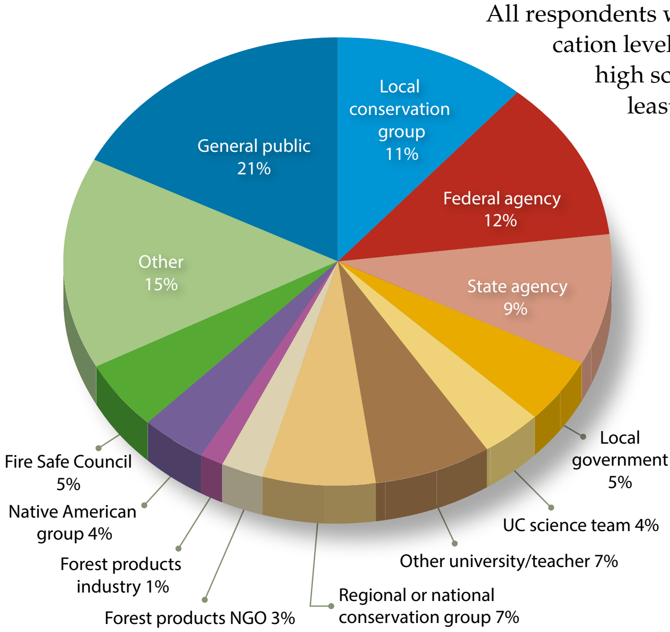

Fig. 4. Percentage of survey respondents who affiliated with predetermined groups in 2010.

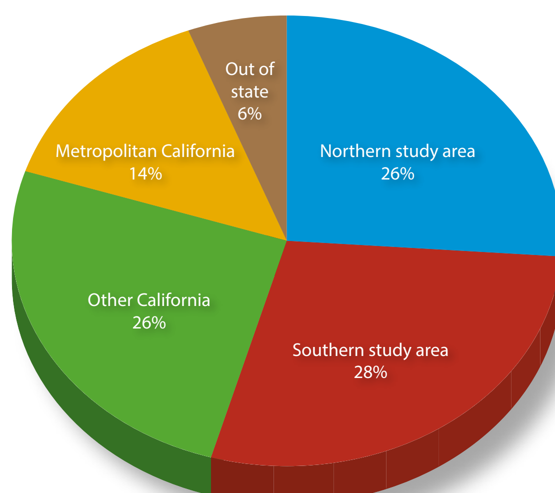

Fig. 5. Residence characteristics of 2010 survey respondents.

not an explicit goal of the project, was shared by over one-third of respondents.

Shared understandings. The development of shared norms and understandings is argued to be key to successful teamwork among participants with divergent perspectives (Sulak and Huntsinger 2012). The goal is to deconstruct polarizing issues (Arnold et al. 2012) and create a hybrid culture with a common language (Sulak and Huntsinger 2012). To these ends, well-structured and -organized meetings that respect diverse sources of knowledge are important; they can create an environment conducive to developing such shared understandings (Arnold et al. 2012).

Workshops on collaborative adaptive management were held to help SNAMP participants learn communication strategies for productive meetings and to create a shared language to help build the long-term relationships to support learning and adaptation (Stringer et al. 2006). For example, the variety of definitions of adaptive management in Forest Service literature was discussed, and then compared to the science team's and stakeholders' definitions.

Multiple formats for sharing research plans and results and getting feedback were used in the SNAMP process, as has been shown beneficial in other studies (Arnold et al. 2012; Stringer et al. 2006) (fig. 3). UCCE continued to create new events and formats to address needs that came up as part of the iterative process (Stringer et al. 2006).

The survey indicates general satisfaction in this area of shared understandings, with strong agreement that the SNAMP process promoted learning and that the meetings were well organized (fig. 6).

Perspectives on forest health. To assess differences in stakeholder perspectives on subjects where learning and shared understandings would be important to perceptions of success at the end of the project, a series of questions was focused on forest health. The survey asked what indicates a healthy forest. More than 80% of respondents agreed that forest resilience, ecological processes and diversity, and regular, natural fires were indicators of forest health (fig. 7). More than half agreed that a healthy forest should sustainably produce timber and have well-spaced trees without debris buildup.

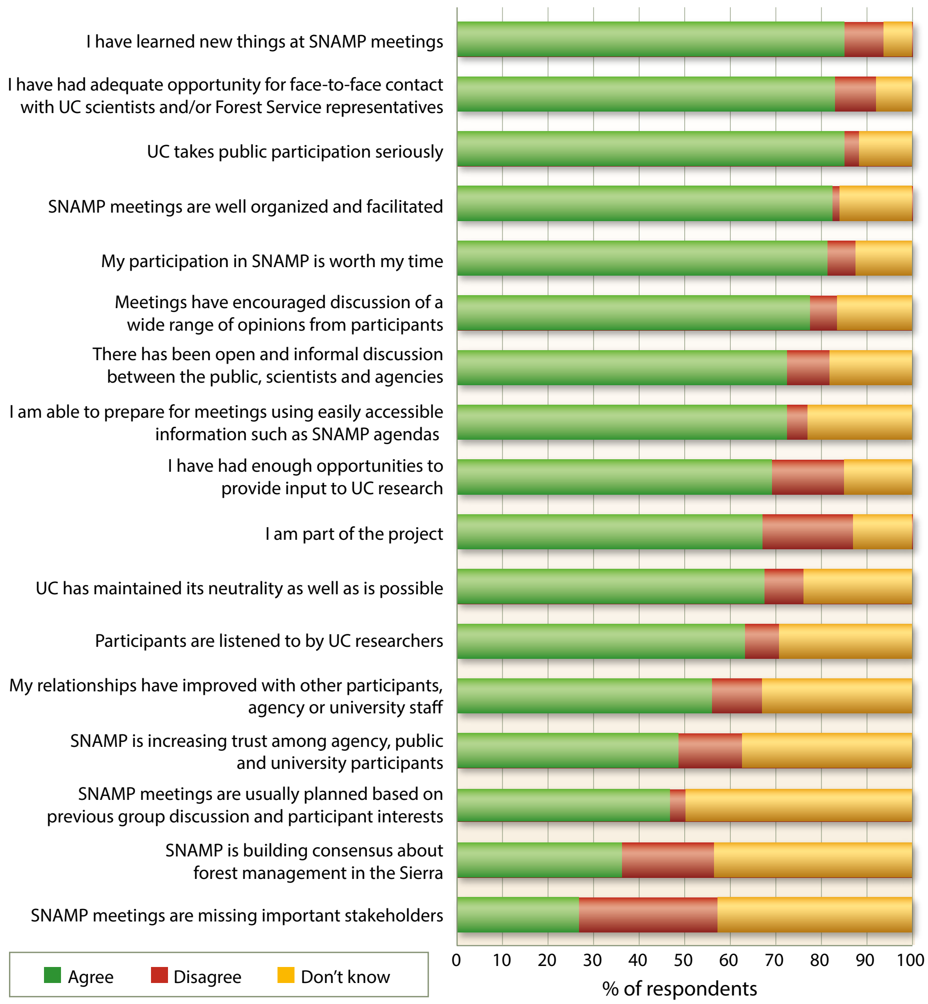

Fig. 6. Percentage of respondents to the 2010 survey who agreed that "Because of the way UC has facilitated participation for the SNAMP project so far, I think that . . ."

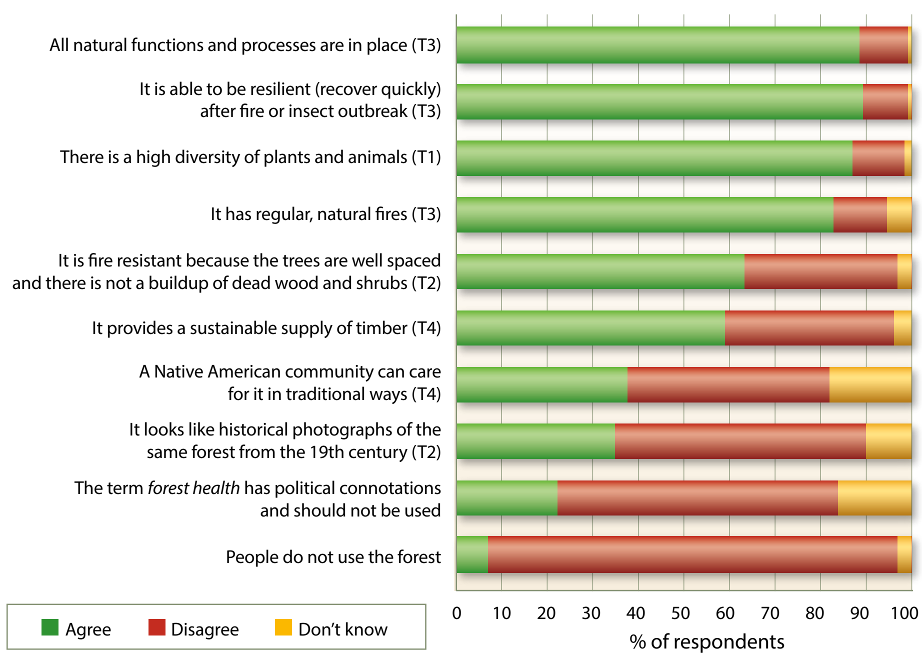

Fig. 7. Percentage of respondents to the 2010 survey who agreed that "A forest is healthy when . . ." and the major themes: building biodiversity (T1), matching historical conditions (T2), promoting ecological processes (T3) and emphasizing active management (T4) (Sulak and Huntsinger 2012).

Important to more than one-third was matching the look of a forest to its historical conditions; a similar number cared about Native American stewardship. Over a fifth of respondents agreed that the term *forest health* has political connotations. Less than 10% agreed that a forest is healthy when "people do not use it."

The response options were based on earlier interviews with a broad spectrum of participants conducted as part of the research approach (Sulak and Huntsinger 2012). The interview research conducted by the public participation team at the project outset found that definitions of forest health could be clustered around four general themes, though they do overlap: building biodiversity, matching historical conditions, promoting ecological processes, and emphasizing active management (Sulak and Huntsinger 2012). The email survey responses agreed most strongly with promoting ecological processes and building biodiversity, with fire and fire resistance as part of those processes (fig. 7). Active management, as reflected in maintaining a sustainable timber supply and Native American stewardship, and matching historical conditions, including spacing the trees, were also indicators of forest health for many respondents. Like the email survey respondents, very few interviewees stated a preference for a hands-off approach, and management was often mentioned as important to a healthy forest. Results from a follow-up survey at the end of the project will show whether notions of forest health changed during the SNAMP process.

Shared decision making. There are two major kinds of decision making within SNAMP, decisions about research made by the science team and decisions about management made by the Forest Service. Both groups have strong constraints on sharing decision making with stakeholders. These limitations are challenging to stakeholders but understanding them is key to SNAMP's success.

SNAMP fits into the category of top-down — rather than bottom-up, or grassroots — participatory adaptive management projects. A top-down project generally has a less organic set of relationships to begin with, making it harder to build and strengthen connections among participants, and a less democratic governance structure. Arnold et al. (2012) in their review of adaptive management processes point out that although under these conditions decision making is "often loosely equated to agreement by all parties, it more accurately reflects the perspective of stakeholders with the most power and a lack of active opposition by others."

The science team works with UCCE to seek public and agency feedback on research decisions. However, researchers hold that they must keep to the scientific practices set by their peers, which limits their ability to use all suggestions. At the behest of the public participation team, they agreed to make their decisions transparent and to provide a clear explanation when stakeholder input was not used. For example, in an online discussion board post, a public participant suggested study of a nearby severely burned area. A researcher explained that this could not fit the timeframe, budget and objectives of SNAMP or result in better management information, because there was no pre-fire data available from the site and the high-severity burn was not comparable with the prescribed fires used in SNAMP.

The science team held as a principle that public input leads to better research as well as management, but in actuality gave the public a consultative role rather than sharing decision making collaboratively. Stringer et al. (2006) state that power sharing can remain elusive in settings dominated by scientists and managers. To avoid some of the misunderstandings that have been a problem in other participatory management efforts (Wagner and Fernandez-Gimenez 2009), this limitation was made clear to all participants at the outset of the project. The survey indicates a positive relationship with the science team: The majority of respondents valued the learning opportunities, open discussions and face-to-face interactions with scientists and agreed that they showed interest in stakeholder input; respondents felt "part of the project" (fig. 6).

In the Sugar Pine project area, SNAMP scientists studied the effects of thinning treatments on Pacific fisher (*Martes pennanti*) habitat quality and collected data on fisher survival and behavior within four watersheds.

As for the Forest Service, it has been argued that full decision making authority cannot be devolved or abdicated outside of Congress's reach (Coggins 1999; Moote and McClaran 1997). This possible hurdle was raised at the beginning of the project in 2005, and again in April of 2008 by many participants in SNAMP workshops because of their aspiration to have true comanagement with the Forest Service, including shared decision making. Some participants were concerned that their contribution over the many years of SNAMP may ultimately be "a waste of time" if they cannot have more assurance that SNAMP results will be used by the Forest Service.

The perception that participants risk wasting resources and time has been expressed numerous times during participatory projects led by land management agencies. One comprehensive study of collaborative projects found that "collaboration experience was negatively associated with trust, indicating that participants with past experience in many collaborative groups were less trusting of other participants than participants with little previous collaborative experience" (Wagner and Fernandez-Gimenez 2009).

The Forest Service extends a fundamentally consultative role to SNAMP participants, with the expressed intention of adhering to the results of the project. The institutional limits to power sharing are challenging, but different aspects of an adaptive management program may have different levels of public involvement (Stringer et al. 2006); the diverse

SNAMP formats allowed a collaborative approach when possible — for example, learning about and interpreting findings in integration meetings could be more collaborative than could forest management decisions. Field trips and group meetings provided for a free exchange of information that informed all participants, while providing feedback to scientists and managers.

Development of trust. In the third year of SNAMP, to develop trust and increase stakeholder input into the project, each research team began to hold annual integration meetings, where they shared and discussed their research progress with the public. The intention was to encourage detailed two-way conversations between researchers and the public, develop a committed core membership within SNAMP and collaboratively address the transition between scientific results and management action. There had previously been large public meetings quarterly, with a broader and more general agenda, but public feedback indicated preference for more intensive modes of interaction.

In 2010, more than 80% of respondents felt that participation in SNAMP was worth their time. A large majority of those who did not "agree" that relationships were improving, consensus was being reached or trust was being developed responded that they simply "didn't know" yet, at the time of the survey (fig. 6). The closing survey at the end of UC's participation will provide more information about stakeholder response to the process once the analysis is finished.

Critical to stakeholders' long-term views of the project will be closing the adaptive management loop. An adaptive management cycle is considered complete when research results are used in future management decisions. This closure will largely take place after the UC role in SNAMP ends.

Remaining questions

Because of SNAMP, there is more clarity and understanding about forest management among different stakeholder groups, but how SNAMP information will be applied in the future, and whether stakeholders will continue as informed participants working with the Forest Service, is uncertain. It is known that the science team cannot co-conduct research, and the Forest Service cannot comanage the forest, and the public's role is constrained by the scientist's adherence to perceived scientific norms and the Forest Service's legal responsibility for decisions. Around these givens, however, there are indications of improved relationships and shared understandings; according to most of the survey respondents, SNAMP encouraged learning and opportunities for participation. The question is whether this learning and relationship formation will be enough to support Forest Service use of SNAMP results as it implements fuels reduction projects and to sustain continued learning and adaptation.

SNAMP participants remain concerned about whether the research results will be used in future management decisions. Public participation team researchers now hypothesize that the participation of a third party like UC in Forest Service adaptive management programs can help to reduce the concerns of stakeholders and increase the social legitimacy of decisions. More exploration is needed of UC's capacity as an independent research and outreach provider to mitigate a lack of trust and consensus, and an imbalance of power, between the public and land management agencies and among stakeholder groups. Also crucial is to explore what other opportunities for third-party participation there are in public land adaptive management projects. CA

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Cooperative, cross-boundary management facilitates large-scale ecosystem restoration efforts

by Erin Kelly *and* Jonathan Kusel

In California and across the United States, landscape restoration projects often require cross-boundary cooperation, though successful examples are rare and not well understood. This case study describes the Burney Gardens timber harvesting plan, a cooperative, cross-boundary meadow restoration project undertaken by private corporate forest landowners in Northern California as part of a larger collaborative restoration effort. The project is notable because it (1) received institutional support — both financial and political — from federal, regional and local sources and (2) engaged a diverse group of stakeholders in pre-project planning with multiple agency partners. This approach enabled the project plan to pass through the rigorous California regulatory system in an unusually rapid fashion despite its complexity. The collaborative model of the Burney Gardens project is relevant to other restoration efforts, particularly as diverse ownerships across the West implement large-scale projects that cross property boundaries, including those of federal and private lands.

Increasingly, large-scale restoration projects have become a priority for land managers in the United States, leading them to look beyond reserved lands (e.g., national parks) to the mix of private and public lands that characterize many watersheds (Lindenmayer and Franklin 2002). Policies at the state and federal levels have begun to address cross-boundary management — management that occurs across lands owned by different entities, with treatments implemented regardless of ownership type — facilitating both grassroots-based cooperative institutions, such as watershed councils (Rickenbach et al. 2011), and policies aimed directly at federal land managers, such as the 2009 U.S. Forest Service Collaborative Forest Landscape Restoration (CFLR) Program. U.S. Department of Agriculture Secretary Tom Vilsack stated that the U.S. Forest Service must work on restoration across property boundaries in an "all-lands approach" (USDA 2009), pointing toward the importance of land management that transcends ownership boundaries. Examples of successful cross-boundary restoration projects, however, are limited because of disparate environmental policies, economic motivations and resource (financial, technological, etc.) capacities of different ownerships (Charnley 2006).

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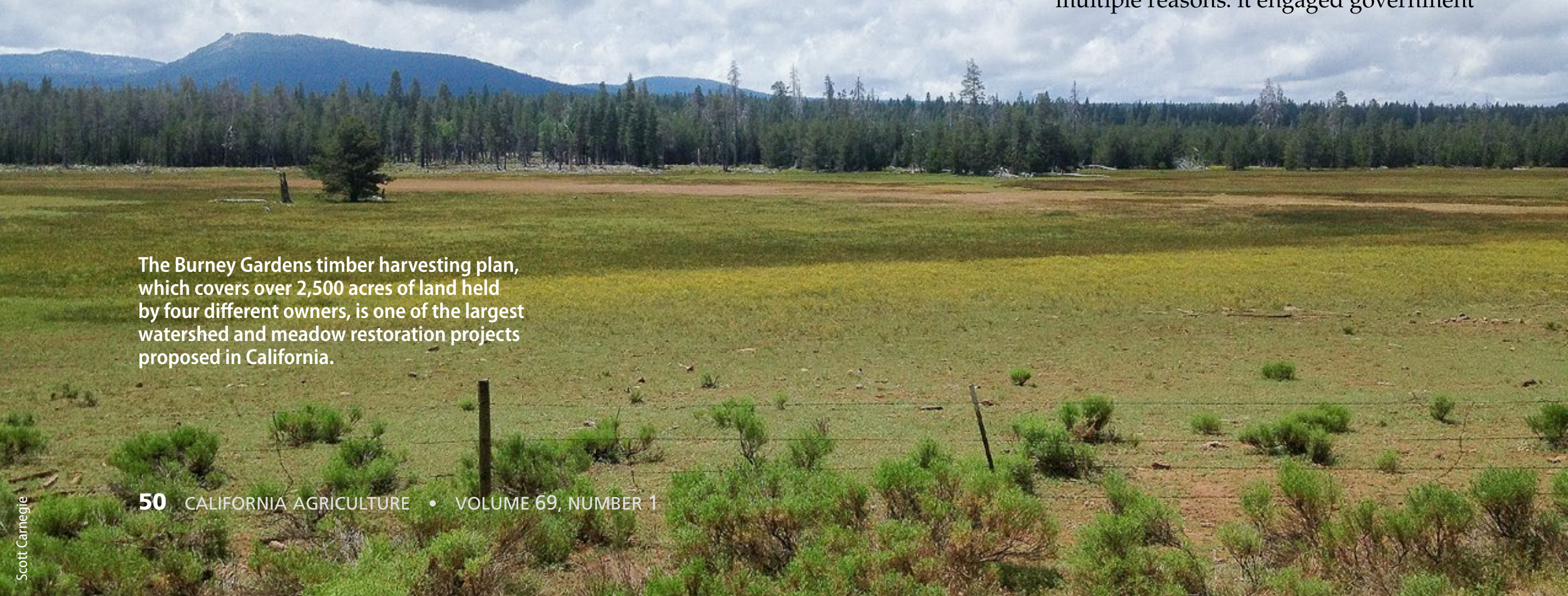
The Burney Gardens timber harvesting plan (THP) is a cross-boundary, cooperative restoration plan developed by four private forest landowners in Northern California (Shasta County) that are part of a CFLR group. The THP was developed to restore a degraded meadow system being encroached by lodgepole pine (*Pinus contorta*), now growing in overstocked conditions as a result of fire suppression. Watercourses within the THP are degraded due to channelization and loss of riparian vegetation; this has resulted in erosion and insufficient shade. The Burney Gardens THP is now one of the largest watershed and meadow restoration projects ever proposed in California; restoration treatments include removal of lodgepole pine from the meadow as well as channel restoration. Some treatments have begun, such as thinning treatments around edges of the meadow, though much work remains (hydrological treatments are expected to begin summer 2015).

The Burney Gardens THP is notable for multiple reasons: it engaged government



The Burney Gardens timber harvesting plan, which covers over 2,500 acres of land held by four different owners, is one of the largest watershed and meadow restoration projects proposed in California.

Scott Carnegie

agencies and other stakeholders in extensive up-front planning; it received the support of a variety of organizations; it fostered trust and shared norms among a diverse group of stakeholders; and it enabled the CFLR group to provide evidence of a successful project, which was necessary to fulfill CFLR program mandates and leverage further funding. Furthermore, the plan was approved by regulatory agencies in less than a month, a remarkable achievement for a timber plan in California, where such plans may take over 6 months from submission to approval. The THP and associated restoration work could have generated conflict among agency review team members and the general public; its success in fostering cross-boundary cooperation and winning rapid approval make it a model worth understanding.

Reasons for restoration

Forest ownership in the United States is multifaceted, with widely varying management motivations, financial considerations, governance structures and regulatory standards. In the United States, 56% of forestland is privately owned, and 44% is publicly owned. In California, like much of the West, public ownership is higher (table 1), totaling roughly 60%. The remaining 40% of forestland is private, with 14% owned by corporate (industrial and investor) entities, and 26% owned by noncorporate entities, or "family" forest owners. If coordinated restoration projects are to be successful, we must understand the conditions that encourage private landowners to work across property boundaries. This case study focuses on private corporate landowners, a group largely overlooked in previous studies on cross-boundary collaboration.

A number of studies suggest that private landowners are willing to work cooperatively for various restoration objectives (Creighton et al. 2002; Ferranto et al. 2013; Fischer and Charnley 2012; Jacobson 2002; Rickenbach et al. 2011). Most of these studies focus on hypothetical scenarios, asking landowners whether they would work across property boundaries rather than how they can create and implement projects that span ownerships. Importantly, most studies have focused on noncorporate forest owners, whose management motivations are widely recognized as multifaceted (e.g., Butler and Leatherberry 2004; Creighton et al. 2002).

Corporate landowners' motivations are less well studied and typically described in terms of economic optimization and return on investment (e.g., Wigley and Sweeney 1993), which suggests that corporate landowners have little interest in cross-boundary restoration projects. In one of the few studies to present an alternative perspective, Brody et al. (2006) surveyed representatives of 38 forest companies and found a variety of reasons for participating in restoration projects, including building relationships and trust with outside stakeholders, avoiding litigation and increasing personal satisfaction for managers.

Burney Gardens THP was approved in a less than a month, a remarkable achievement for a timber plan in California, where such plans may take over 6 months from submission to approval.

Private forest planning in California

THPs are the key environmental documents through which forest managers secure approval for private timberland management in California; Burney Gardens project collaboration took place largely through this permitting mechanism. The plans are developed according to the California Forest Practice Rules, which regulate forestry in the state through one of the most rigorous private forest regulatory frameworks in the world (McDermott et al. 2007). THPs are written by foresters certified by the state of California and provide an opportunity for public input on private forest management projects.

As part of the approval process, THPs are reviewed by multiple state agencies, including the Department of Forestry and Fire Protection (Cal Fire), regional water quality control boards and the California Department of Fish and Wildlife. In a majority of cases, a preharvest inspection is required, wherein the multi-agency review team assesses a plan in the field. Questions are directed to the forester, who is obligated to "satisfactorily" respond to these questions prior to Cal Fire's approval of the plan. A THP is often subjected to several rounds of reviews, each typically requiring modifications.

The Burney Gardens project was the first THP to take advantage of a 2012 change in the Forest Practice Rules called the Aspen, Meadow, and Wet Area Restoration rule modification (Aspen and Meadow Rule). This rule was implemented in part because landowners and stakeholders from the Burney Gardens region identified regulatory hurdles to meadow restoration projects. The new rule was developed in recognition of changes to natural disturbance processes, particularly fire suppression, that resulted in conifer encroachment in meadows, such as those in the southern Cascade region of Burney Gardens. These meadows provide vital habitat and maintain hydrologic processes and water quality, and approximately 40% of all meadows in the region are located on privately owned lands and under the purview of the California Forest Practice Rules (Gross and Coppoletta 2013).

Under the new Aspen and Meadow Rule, managers were allowed to bypass

TABLE 1. Forest ownership patterns in California and the United States, 2007

Region	All forest lands	Total public* (% of total)	Private corporate (% of total)	Private noncorporate (% of total)
	Thousand acres			
Burney-Hat area	369	230 (62%)	112 (30%)	26 (7%)
California	32,817	19,614 (60%)	4,603 (14%)	8,600 (26%)
US total	751,228	328,199 (44%)	138,120 (18%)	284,908 (38%)

* Public lands include federal, state, and county and municipal lands.
Data from Smith et al. 2009 and USFS 2011.

In 2012, the Forest Practice Rules were modified in recognition of changes to natural disturbance processes, such as fire suppression, that led to conifer encroachment of meadows. The new rule was implemented in part because landowners and stakeholders from the Burney Gardens region identified regulatory requirements that hindered large meadow restoration projects.

Forest Practice Rules requirements for conifer regeneration such as size restrictions (generally 40 acres) and adjacency restrictions, which prohibited adjacent clear-cuts for 5 years. In large meadow restoration projects like Burney Gardens, these requirements previously limited treatment size and forced landowners to submit THPs with "alternative prescriptions" that were time-consuming and costly (BOF 2011). The new rule created a more time- and cost-efficient process with the goal of promoting large-scale restoration.

Interviews with stakeholders

The authors participated in meetings for the Burney-Hat Creek Community Forest and Watershed Collaborative Group (Burney-Hat Group) and its private land subcommittee, which developed the Burney Gardens THP. The second author initially worked to bring together the Burney-Hat Group and encouraged state agencies to work with landowners to develop an all-lands project and THP.

We conducted interviews (n = 16) with the land managers for the private forest companies (n = 4), and with state and federal agency personnel (n = 9), funding agencies (n = 1) and other collaborative group members (n = 2). We selected interviewees based on their involvement in the Burney-Hat Group or because of their participation in the Burney Gardens THP. Interviews were semi-structured and topics depended on interviewee expertise, regarding either (1) the creation of the Burney Gardens THP, (2) the role of Burney-Hat Group in supporting the THP or (3) the creation of the Aspen and Meadow Rule. Interviewees were contacted in person or via email. During interviews, notes were taken, and were later transcribed and then analyzed through coding for thematic content per Strauss and Corbin (1998). Coding was done using NVivo software (QSR International, Doncaster, Australia) with codes assigned to interview segments to organize and understand interview data.

Burney Gardens THP development

The Burney Gardens THP encompasses a large, mixed-owner acreage, totaling 2,530 acres — about five times the average size of a THP for the region (Thompson and Dicus 2005). Conifers, mostly lodgepole pine, had encroached 1,360 acres of meadow, leaving only 140 acres without lodgepole intrusion. The THP called for removal of conifers from the meadow, and single-tree selection harvest (the removal of individual trees in commercial operations) of forested lands from the remaining 1,170 acres.

Though all four landownerships involved in the THP are corporate, their ownership structures are diverse. Sierra Pacific Industries is industrial, with both forest products facilities and timberland; Pacific Gas and Electric and Fruit Growers Supply Co. own timberland as single components of larger corporate structures; and W.M. Beaty is a consulting forestry group that manages land for other landowners. A consulting forester under contract to W.M. Beaty wrote the Burney Gardens THP.

Funding and institutional support. In 2009, the Shasta County Resources Advisory Committee (RAC), established under the Secure Rural Schools and Community Self-Determination Act (H.R. 1424 §601), recommended funding for development of a collaborative group that would succeed in implementing forestry projects across several key watersheds without regard to land ownership. The RAC wanted to launch a "legacy project" to continue to advance its work on a larger scale and in a more comprehensive manner. This new collaborative became the Burney-Hat Group and was organized by Todd Sloat, watershed coordinator for the Fall River Resource Conservation District, with help from the U.S. Forest Service Hat Creek district ranger and the second author. Membership included environmental, corporate, tribal and governmental stakeholders.

The Burney Gardens THP was one of the first projects to receive support from the Burney-Hat Group; initial work on the plan began soon after the group was launched. The group's support resulted in RAC funding for THP development and generated political backing from the community for the project, which helped alleviate distrust between traditional opponents, such as members of environmental nonprofits and corporate forest managers. One corporate land manager said the project succeeded because of the community's support, and a member of an environmental nonprofit who was wary of many logging projects attributed the THP's success to the work of the landowners who "got together for the sake of the meadow." In addition, there was broad consensus within the group about the need for tree removal to restore the meadow (Burney-Hat Group 2011).

Participants from the Burney-Hat Group indicated that previous restoration efforts, especially on public lands, were not fruitful and caused frustration for neighboring landowners and stakeholders. A participating forester stated, "Rather than just sit there and plan, talk to ourselves, we needed something tangible." Most interviewees indicated that the Burney Gardens THP was a model for future projects. According to one representative of an environmental nonprofit, "We want it to be a good example of what a restoration project should look like." As likelihood of project success increased, the project grew from a few hundred acres to its final size of over 2,500 acres.

In addition to the catalytic RAC funding, Burney Gardens THP development received support from state agencies including Department of Conservation and Sierra Nevada Conservancy; federal agencies including Natural Resource Conservation Service and U.S. Fish and Wildlife Service; and the private lands manager and utility company Pacific Gas and Electric. The THP cost about $90,000 to prepare, which included biological and archaeological assessments and document preparation, along with hydrologic restoration planning and permitting.

The Burney-Hat Group used the Burney Gardens THP to demonstrate that it could work across ownership boundaries. In 2011, the Burney-Hat Group won the Region 5, U.S. Forest Service Regional Forester's Award for All Lands Management. In early 2012, the Forest Service designated the Burney-Hat Group and the Lassen National Forest's Burney and Hat Creek landscape (369,000 acres total) as one of three CFLR projects in California. As part of this designation, the Burney-Hat Group received $10 million to be spent over 10 years for landscape restoration on national forest and adjacent private lands, and for improvement of community socioeconomic health. In this manner, the Burney Gardens project leveraged support and expanded landscape restoration possibilities.

Regulatory agencies and THP process review. The process review for development of the THP demonstrates the extent of upfront, pre-project planning that was both unusual and essential to its success (fig. 1). In contrast to the process for a typical THP, in which a forester submits a plan to Cal Fire and then receives and responds to suggestions from multiple regulatory agencies, the Burney Gardens THP grew out of a July 2011 meeting called by the Burney-Hat Group working with the central Sierra–based Amador Calaveras Consensus Group and the Sierra Nevada Conservancy. State and federal agencies were asked to participate in this meeting to discuss advancing all-lands work. Burney-Hat Group members

Members of the Burney-Hat group organized field trips and discussions with government agencies to inform development of the THP. The direct meetings and informal relationships that developed over time contributed to trust and, ultimately, the ability of both private landowners and agency personnel to effectively work together.

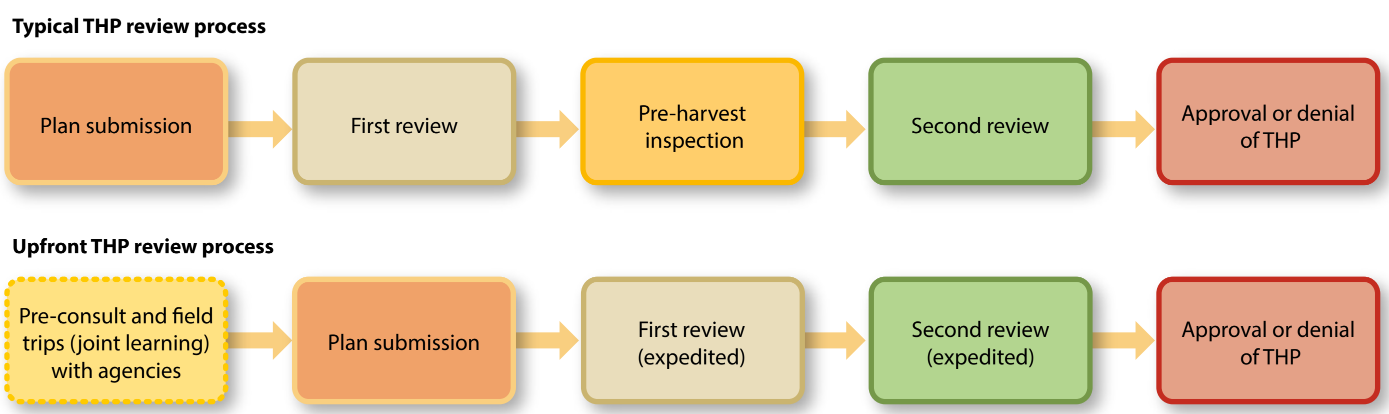


Fig. 1. The top row illustrates a typical THP review process, with multi-agency reviews of submitted plans. The second row illustrates an upfront process, with agency input into plan creation.

Left, some of the remaining meadow at the Burney Gardens site.

contacted review agencies directly to ask whether they would engage in preconsultation discussions and organized field trips to inform development of the THP (fig. 1). With support from a Cal Fire deputy director, who had at the July meeting agreed to participate, other agencies joined the field trips and discussions. Site visits with land managers and agency staff continued through the fall of 2011.

The passage of the Aspen and Meadow Rule, coupled with support from mid- to high-level officials within the regulatory agencies, provided impetus to local agency personnel to engage with and support the Burney Gardens THP. Instead of responding to comments from agencies after the bulk of planning was completed, foresters were able to incorporate agency concerns into plan development. Moreover, the direct meetings and informal relationships developed over time contributed to trust and, ultimately, the ability of both private landowners and agency personnel to effectively work together. Although upfront work for the THP was extensive and involved more field visits than a typical THP, interviewees felt it resulted in a better plan and proved to be more efficient than the typical review process.

Local biomass capacity. For the private land managers, a shared sense of the need to manage the land base and mutual familiarity with timber management and planning made partnership work. However, the meadow restoration described in the Burney Gardens THP can only be realized if the THP is fully implemented, and as of winter 2015 there remain several barriers to completing the work, as well as future all-lands work in the Burney-Hat landscape. Approximately 113 acres of single-tree selection have occurred thus far, but none of the meadow restoration work has been completed.

The most significant barrier for Burney Gardens as of 2015 is the lack of biomass capacity in the local area. Small diameter material removed from restoration projects such as the Burney Gardens THP has limited economic value. Two active biomass facilities remain in close proximity to the project area, but only one accepts biomass from outside entities. The amount of material generated by the Burney Gardens project is expected to saturate the limited local market, depressing prices that are already low. With limited economic utility for biomass material, less restoration is possible.

New policy directions

The Burney Gardens THP demonstrates that large-scale restoration projects can be successfully developed on private lands involving multiple owners — in this case, multiple corporate-owned private forestlands. The circumstances surrounding the creation of the Burney Gardens THP point toward policy directions to facilitate cross-boundary management, in particular (1) nested, multi-scaled institutional support at the regional, state and federal levels and (2) coherent, upfront project planning.

Corporate landowner motivations. Like Brody et al. (2006), we found motivations for restoration that encompassed more than economic optimization. Clewell and Aronson (2006) described five types of landowner motivations for restoration, including technocratic, in which legal requirements mandate restoration activities; biotic, such as biodiversity protection; heuristic, in which restoration is educational; idealistic, in which humans seek to atone for degradation; and pragmatic, in which ecosystem services are valued and enhanced. Corporate landowners' restoration objectives are typically driven by economic self-interest and technocratic, or law-abiding, motivations.

The Burney Gardens project showed that corporate landowner motivations can exceed narrow self-interest. While corporate landowners participated in part to convince the Forest Service to treat its overstocked forests as part of the CFLR program — resulting in reduced risk of fire moving from federal forests to their private lands — we also found that biotic and idealistic reasons were put forth by the corporate land managers in describing the project as "the right thing to do" to achieve a healthier landscape. Pragmatic reasons, such as water quality improvements and improved grazing, were also cited as important. Even heuristic reasons were cited as motivation for the project, as the corporate land managers wanted to demonstrate the efficacy of meadow restoration and the success of the collaborative group in moving from project concept to implementation.

These findings suggest that future restoration projects involving corporate landowners may encourage participation through more than legal requirements or economic incentives. Whether because of the landowners' desire for social license and approval from neighbors or because of individual managers' sense of stewardship, motivations for participating in joint landscape management and restoration

As a result of conifer encroachment on 1,360 acres of meadow, watercourses have little or no riparian vegetation and have been channelized (*right*), resulting in increased erosion and water quality degradation.

are more complex than previously granted. There is need for additional exploration of the impetus behind corporate landowner behavior, especially to promote corporate landowners as partners in restoration projects within the all-lands management goals of the U.S. Forest Service.

Nested institutional support. The creation of the Burney Gardens THP was successful because of a nested series of supportive institutions at multiple levels (from regional to federal), confirming previous findings (Epanchin-Neill et al. 2010; Ostrom 2012; Rickenbach et al. 2011). Epanchin-Neill et al. (2010) proposed bottom-up, middle-level and top-down institutions, each with different roles in a cooperative partnership, with middle-level organizations facilitating communication and mediating between the managers on the ground and governmental agencies. In this case, the Burney-Hat Group and the Fall River Resource Conservation District filled this middle-level role, which was further embedded in and supported by funding from the Shasta County RAC and the federal CFLR program. Within the state of California, the Burney-Hat Group was able to garner top-down support from several agencies, most notably Cal Fire. This support enabled agency personnel to take risks with an unusual THP review process that included unconventional practices and a comparatively large planning area.

The Burney Gardens THP is also an important example of garnering ground-level, local support. Many top-down restoration projects have faced hurdles because local voices have been excluded; for example, Barr and Sayer (2012) point to REDD+ projects in the developing world as marginalizing local communities, resulting in perverse incentives to degrade landscapes outside project areas. The Burney Gardens THP, on the other hand, is a rare attempt — with consent from corporate landowners and managers — to incorporate public input into private management action. Rather than simply offering a plan for comment, the Burney Gardens project was formulated with agency and Burney-Hat Group member participation. Restoration became a process of reintegrating people with their landscape, in contradiction to the view that ecological integrity exists in the absence of human management (Rikoon 2006). One result of Burney-Hat Group member inclusion was increased respect and support for private land managers, including improved understanding and respect for the hurdles they face.

Upfront planning. The Burney Gardens THP demonstrates the power and efficacy of upfront planning. Rather than bringing in state agencies after THP completion, as is normally the practice, Burney Gardens THP involved agencies early in the project planning process. This early engagement, or pre-project consultation, laid the groundwork for communication and openness and subsequent integration

***Above*, an example of lodgepole pine encroachment and a watercourse without hardwood riparian vegetation.**

of agency concerns into the plan that was submitted. Project designers were able to proactively address concerns through integrative discussions among multiple landowners and agency members, rather than leaving individual foresters to respond to agency comments after plan submission. Instead of trying to advance a project that would pass inspection but produce diminished restoration results, upfront and multi-stakeholder planning enabled the Burney THP to incorporate diverse goals and tackle multiple issues. The result was a coherent, large-scale restoration project that included both commercial timber production (through single-tree selection harvests) and meadow restoration.

These findings have implications for public land managers on federal lands, whose energies are too often focused on procedural issues associated with public processes mandated by with the National Environmental Policy Act (NEPA) and potential litigation. According to Mortimer et al. (2011), this situation has resulted in delayed decision making and led to excessive risk aversion within the agency. Upfront planning for NEPA documentation is a relatively new tactic for the U.S. Forest Service, which has long presented the public with pre-digested alternatives and a preferred option developed without stakeholder involvement. With upfront planning, the Forest Service could incorporate the views of stakeholder groups into its projects, potentially leading to a less adversarial NEPA process, successful project implementation and trust building for subsequent management projects.

Future research and next steps

As the all-lands approach is extended to more multi-jurisdictional landscapes, federal land managers will need to consider ways to support and integrate private landowner participation. Private landowners join collaborative groups when the benefits outweigh the costs of meeting and negotiating outcomes (Lubell et al. 2002). In this case, transaction costs were reduced through the creation of a supportive network of organizations that provided both funding and political backing for restoration, and extensive upfront planning that allowed the landowners to create a coherent and integrative restoration strategy rather than responding piecemeal to agency concerns.

Although the Burney Gardens project grew out of a multi-jurisdictional landscape group, the project remained focused on private land. Integrating private and federal land management is a needed next step, and one that will likely prove more difficult. The summer 2014 fires that burned tens of thousands acres in the CFLR area, including private land, will challenge and compel partners to not only work through frustrations as a result of losses associated with the fires, but differences in landscape objectives and practices. Though barriers to full completion remain, the Burney Gardens project offers the outlines of success that inform how to develop a more resilient landscape and contribute to socioeconomic vitality of nearby communities. CA

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UC Cooperative Extension works with fire safe councils to reduce wildfires

by Glenn A. Nader *and* Michael De Lasaux

In Plumas, Butte and Yuba counties, UC Cooperative Extension advisors have collaborated with fire safe councils to mitigate the risk of wildfire in local communities. They have determined the educational needs within the communities, obtained grant funding and worked collaboratively with the councils to deliver education and applied research programs that have helped homeowners and landowners take action to reduce their vulnerability to the risk of wildfires. Home structures have been modified to improve their fire resistance, fuel reduction programs have been adopted by local communities and maintained, communities have been mapped for evacuation plans and fuel breaks have been constructed on private and public forestland. Several wildfires, including the Marysville fire in 2006 and the Yuba fire in 2009, were slowed or stopped because of measures taken, showing the value of investment in pre-fire planning and actions.

Fire safe councils are community-based organizations that share the objective of making California's communities less vulnerable to wildfire. They are comprised of a collaborative group of local stakeholders, including federal land managers, state and local fire agency representatives, private forest landowners and community members. They generally meet monthly and work to reduce wildfire hazard through community education programs and fuel reduction projects. Fire safe councils have formed throughout California since the early 1990s and now number more than 100. In Plumas, Butte and Yuba counties, UC Cooperative Extension (UCCE) advisors have worked with local fire safe councils for many years. They have helped to identify needs for science-based information on topics critical to fire risk reduction and delivered the information to the communities in a variety of formats to engage homeowners and landowners in effective pre-fire actions.

Statewide programs

Many homeowners do not know which components of their home are at risk to fire. Deck, roof and siding materials perform differently when exposed to embers and flames. UCCE Advisor Steve Quarles developed research on this topic and educational information for homeowners (Quarles and Beall 2002). In 2005, Quarles and other UCCE advisors and specialists, as members of the UCCE Fire Workgroup, developed a Renewable Resources Extension Act proposal and obtained funding to demonstrate how various structural elements can cause a home to be susceptible to fire and how appropriate modification can improve its resilience. Workgroup members developed model wall and deck units for use in demonstration burns to illustrate common construction assembly weaknesses and possible modifications. In collaboration with local fire safe councils, UCCE used the model in a demonstration burn at several community workshops. In 2006, after being trained by Quarles, UCCE Advisor Glenn Nader (one of the authors of this article) conducted a building burning demonstration for the Yuba County

Online: http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v069n01p57&fulltext=yes
doi: 10.3733/ca.v069n01p57

In 2006, a fire in Marysville (Yuba County) was stopped at the Oregon Ridge fuel break, which was constructed by private timber landowners as part of the Slapjack fuel reduction project.

board of supervisors, which assisted in the creation of the Yuba County fire planner position.

UCCE advisors also developed the UC Agriculture and Natural Resources electronic publication *Home Survival in Wildfire-Prone Areas* (Quarles et al. 2010), which is used by fire safe councils in their community educational programs with homeowners. Some fire prevention actions are as simple as placing wire screens over vents to keep embers from coming into the house and starting it on fire. Others, such as replacing wood shingle roofing with noncombustible composite or metal roofing, can be expensive.

In 2006, in a collaborative effort with UC Berkeley Professor Scott Stephens, advisors obtained funds from multiple sources, including the Sierra Nevada Conservancy, the California Fire Safe Council Grants Clearinghouse and the Renewable Resources Extension Act for field research into the long-term efficacy of past forest fuel treatments. The fuel treatment study used a chronosequence of 52 treated fuel reduction sites and 12 nontreated sites in Plumas, Nevada, Sierra, Lassen and Tehama counties (fig. 1). Previously, the lifespan of fuel reduction treatment effects in mixed-conifer and yellow pine forests was estimated to be roughly 10 years. Figure 2 shows that 8 years and more after fuel reduction, the treatments are still projected by fire models to greatly reduce the chance of a crown fire compared to untreated forest. The study findings (Chiono et al. 2012) "suggest that in the forest types characteristic of the northern Sierra Nevada and southern Cascades, treatments for wildfire hazard reduction retain their effectiveness for more than 10–15 years and possibly beyond a quarter century."

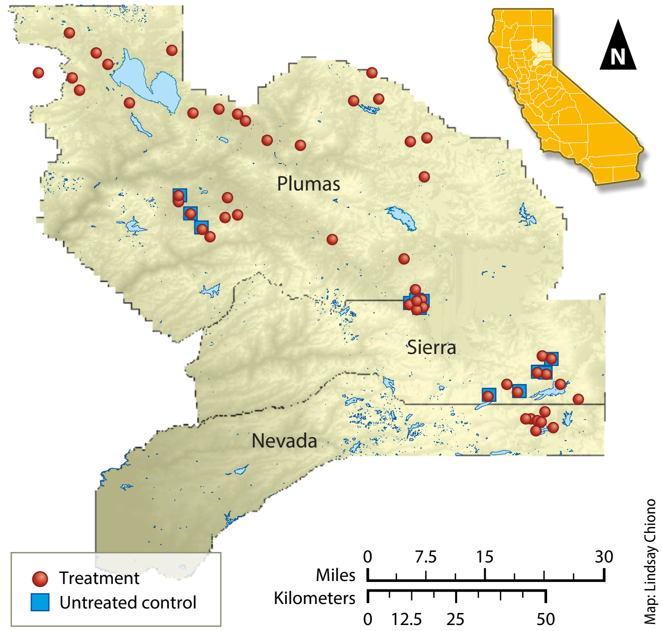
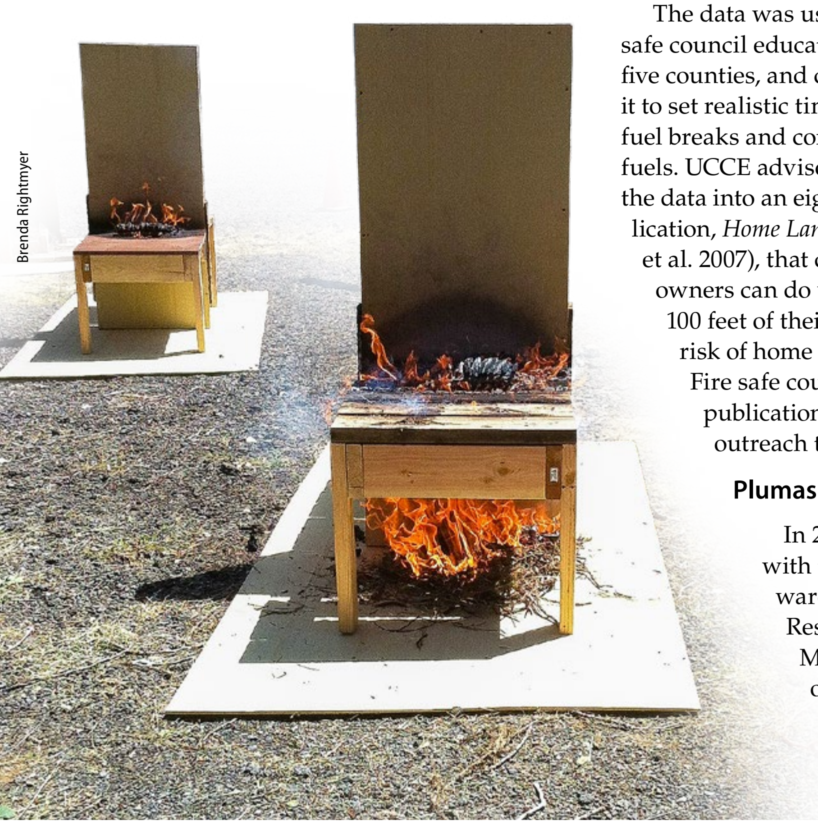


Fig. 1. Study sites for a UCCE and UC Berkeley project examining the long-term efficacy of forest fuel treatments.

The data was used in UCCE-led fire safe council education programs in all five counties, and council members used it to set realistic timelines for monitoring fuel breaks and considering re-treating fuels. UCCE advisors also incorporated the data into an eight-page electronic publication, *Home Landscaping for Fire* (Nader et al. 2007), that describes what homeowners can do with vegetation within 100 feet of their home to decrease the risk of home loss during a wildfire. Fire safe councils have used the publication in their educational outreach to homeowners.

The UCCE Fire Workgroup developed a model home deck unit to demonstrate structural susceptibility to fire and measures to improve fire resistance. Note that the fire has burned through one deck.



Plumas County

In 2001, in collaboration with the Plumas County fire warden, UCCE Natural Resources Advisor Michael De Lasaux (one of the authors of this article) developed the county fire safe council's first grant-funded project. The $100,000 grant from the USDA Forest Service Economic Action Program provided community pre-fire planning and educational firewise consultations and laid a foundation for the council's continuing firewise planning, education and community fuel reduction program.

Firewise planning. Among the earliest accomplishments of the Plumas County Fire Safe Council, which formed in 1998, were efforts to help volunteer fire departments prepare for a wildfire that may threaten their community and require evacuation. Volunteer fire departments are prevalent in rural America, but they are typically challenged to recruit, train and equip their volunteers and rarely are able to conduct fire prevention education programs.

UCCE coordinated several projects in association with the county fire service agencies, including (1) mapping all driveways in the county using global positioning system and geographic information system technology (fig. 3) and (2) planning and developing a map for community evacuation, which involved close collaboration with volunteer fire department chiefs and Plumas County emergency services personnel and also a countywide assessment of the fire hazard for each of the defined communities at risk. The driveway coordinates were used to create map books, which were placed

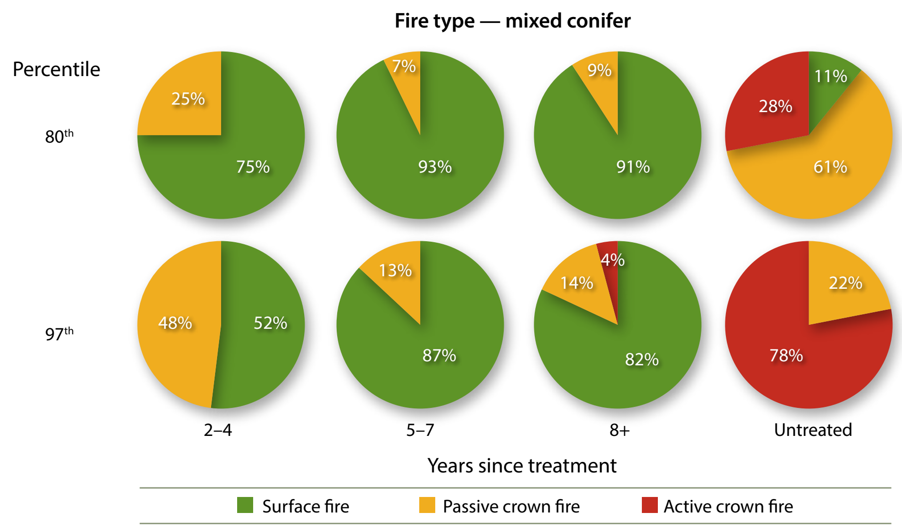
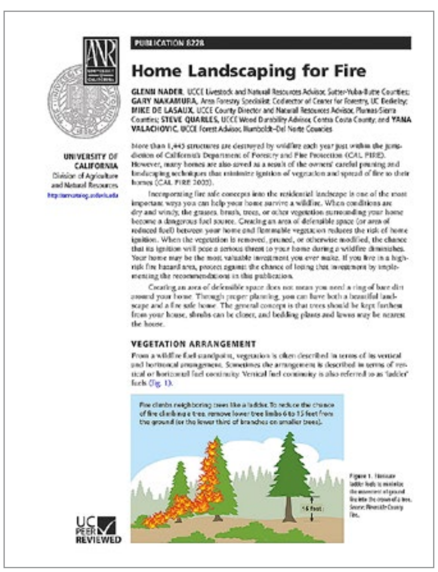


Fig. 2 Fire modeling of fire types on studied fuel reduction treatments. The fire weather index, which is used to predict the risk of weather events causing catastrophic fires, is shown for the 80th and 97th percentiles; the latter is when there is a severe wind event and low moisture levels in the fuels.

in the fire engines of the participating communities. The community fire hazard assessment information has been used in subsequent grant proposals to justify forest fuel reduction treatments in communities at risk.

Firewise education. In 2003, UCCE led the coordination of a series of firewise workshops that focused on community-specific fire safe planning using the format and resources developed by the National Fire Protection Association workshops. More than 50 community



PUBLICATION 8228

Home Landscaping for Fire

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Division of Agriculture and Natural Resources

More than 1,445 structures are destroyed by wildfire each year just within the jurisdiction of California's Department of Forestry and Fire Protection (CAL FIRE). However, many homes are also saved as a result of the owners' careful pruning and landscaping techniques that minimize ignition of vegetation and spread of fire to their homes (CAL FIRE 2003).

Incorporating fire safe concepts into the residential landscape is one of the most important ways you can help your home survive a wildfire. When conditions are dry and windy, the grasses, brush, trees, or other vegetation surrounding your home become a dangerous fuel source. Creating an area of defensible space (or area of reduced fuel) between your home and flammable vegetation reduces the risk of home ignition. When the vegetation is removed, pruned, or otherwise modified, the chance that its ignition will pose a serious threat to your home during a wildfire diminishes. Your home may be the most valuable investment you ever make. If you live in a high-risk fire hazard area, protect against the chance of losing that investment by implementing the recommendations in this publication.

Creating an area of defensible space does not mean you need a ring of bare dirt around your home. Through proper planning, you can have both a beautiful landscape and a fire safe home. The general concept is that trees should be kept farthest from your house, shrubs can be closer, and bedding plants and lawns may be nearest the house.

VEGETATION ARRANGEMENT

From a wildfire fuel standpoint, vegetation is often described in terms of its vertical and horizontal arrangement. Sometimes the arrangement is described in terms of vertical or horizontal fuel continuity. Vertical fuel continuity is also referred to as "ladder" fuels (Fig. 1).

Fire climbs neighboring trees like a ladder. To reduce the chance of fire climbing a tree, remove lower tree limbs 6 to 15 feet from the ground (or the lower third of branches on smaller trees).

UC PEER REVIEWED

UCCE advisors developed an eight-page electronic publication that helps homeowners manage vegetation within 100 feet of their home and reduce the risk of home loss.

members, including county supervisors, volunteer fire department chiefs, realtors and concerned residents participated in these workshops.

Consultations. As part of the 2001 USDA Forest Service Economic Action grant project, De Lasaux coordinated with local fire departments to conduct firewise educational consultations for the public. Volunteer fire departments in six Plumas County communities signed up, and a consultation invitation was sent to nearly 1,700 homeowners, 20% of whom requested a consultation. A version of the National Fire Protection Association Form 299 (NFPA 1997), which provides criteria for fire safe development in areas that may be threatened by wildfire, was modified to suit local conditions and used to guide consultations. About 20% of the properties that were assessed during the homeowner consultations were determined to be a high fire hazard.

Newspaper tabloids. The county fire safe council determined that they would like to provide educational information to the widest audience possible, so a tabloid was developed collaboratively with Feather Publishing, the local newspaper publisher. UCCE led the effort to create the first two editions in 1999 and 2000, using the *Living With Fire: A Guide for the Homeowner* educational materials developed by the University of Nevada Cooperative Extension (Smith 1999). Since 2000, there have been additional tabloids developed with reduced UCCE involvement, demonstrating the long-term impact of UCCE's early work on this project.

Community fuel reduction. The Plumas County Fire Safe Council began development of a community fuel reduction program in 2002 with a demonstration project that treated approximately 63 acres on five parcels. The program was developed by council members in collaboration with De Lasaux, who wrote a detailed description of the processes and policies for landowners contemplating participation in a community fuel reduction program. De Lasaux also drafted a white paper that resulted in the California Board of Forestry developing a timber harvest plan exemption for fuel reduction. Since 2002, more than 4,200 acres have been treated in 25 Plumas County communities with the participation of more than 200 property owners (fig. 4). Grant funds from multiple

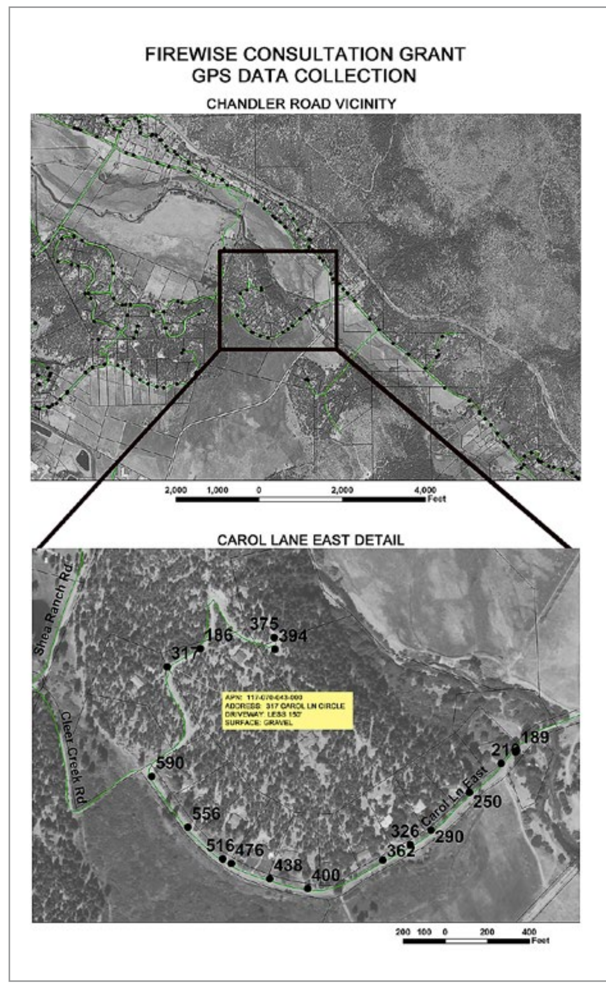

Fig. 3. UCCE coordinated a project to map all driveways in Plumas County using global positioning system and geographic information system technology. Each fire engine in the county has a copy of the map book.

state and federal sources have totaled more than $4.4 million.

De Lasaux monitored more than 70 plots in seven communities to develop information to share with property owners who were considering participation. The plots were assessed before and shortly after fuel reduction treatment. Information collected at each plot included forest stand structure and species composition, canopy cover, surface fuel load, canopy base height, ladder fuel condition and project economics; pre- and post-treatment photographs were also taken.

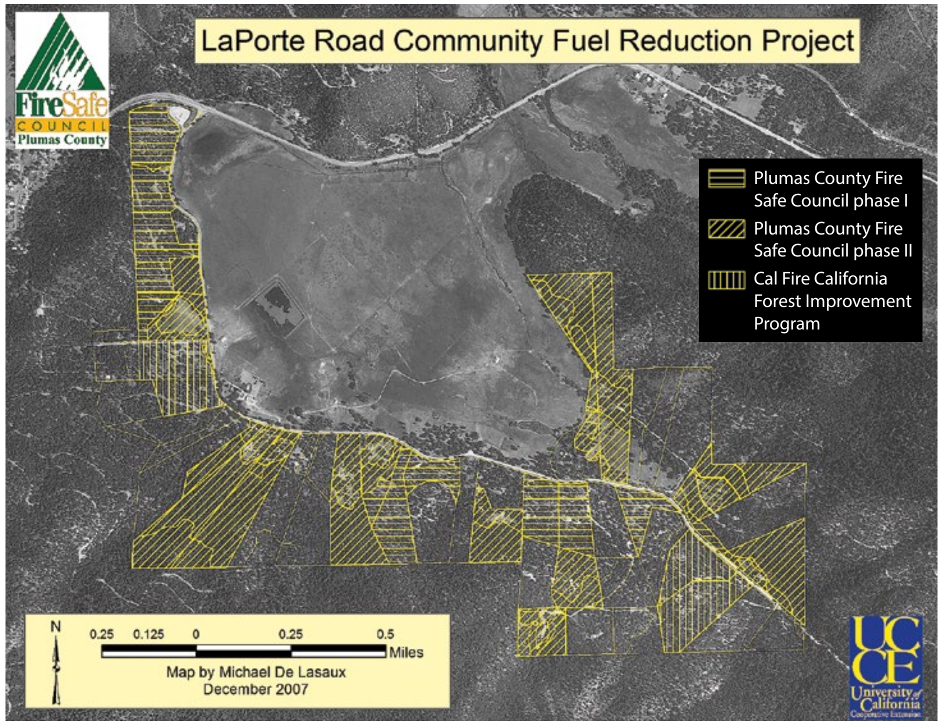

Fig. 4. La Porte Road community fuel reduction map, in Plumas County, showing significant homeowner participation in the project.

Butte and Yuba counties

Fuel reduction maintenance. Advisor Nader obtained a grant to conduct a survey of what motivated homeowners to maintain fuel reduction around their home after they had participated in community fuel reduction projects funded by Yuba Watershed Protection and Fire Safe Council grants. Homeowners who were actively maintaining the fuel reduction were given a list of potential influences to indicate which had an impact on their decision to maintain their property in a fire-safe condition. The results (table 1) helped the Yuba and Butte fire safe councils design their fire safe education to obtain higher participation in fuel reduction.

Sixth-grade wildfire education. Educational efforts that aim to change behavior patterns in society often focus on youth. This approach can also contribute to additive education of parents (Ballard and Evans 2012). Nader used materials from a primary and secondary education course he took called Fire Works at the Missoula Fire Sciences Laboratory in Missoula, Montana, to form the framework of the Butte Fire Safe Council's sixth-grade program, Wildfire in the Foothills.

A grant from the Renewable Resources Extension Act allowed Nader to hire retired teachers to develop a course that addressed state curriculum requirements. It provides teachers with in-service credits and is a complete package that requires no extra preparation work for teachers. The curriculum uses a teaching method called the three R's (relationships, relevance and rigor) to teach lasting knowledge about wildland fire in five lessons, each of which has a distinct learning concept (table 2).

The 2004 pilot program was very successful, with outreach to 90 sixth-grade students in the Paradise Unified School District, which includes Paradise and Upper Ridge. In 2005, the school district taught the program to 490 sixth-grade

More than 70 plots were monitored in seven Plumas County communities before, *left*, and after, *right*, fuel reduction treatments.

TABLE 1. Homeowner motivations for maintaining fire-safe conditions

	%
Concerned about a wildfire destroying my home	96
Desire to keep my environment healthy	93
Recommended by the fire department	47
Required by my insurance carrier	31
Treatment project contract provision to conduct maintenance	22
Other	20
Peer pressure from neighbors	5

TABLE 2. Learning concepts presented in the Butte Fire Safe Council's sixth-grade program, Wildfire in the Foothills

Understanding the role of fire in the foothills.
Residents living in the foothills are responsible for reducing fire risks on their own property.
Local, state and national agencies have plans to help residents prepare for a wildland-urban interface fire before it happens; all family members must understand and be ready to use community wildland fire disaster plans.
A family disaster plan is vital to surviving a wildland fire.
Residents, community groups and public agencies all play important roles during planning, surviving and recovering from a wildland fire.

students. The program is also being offered to 95 students in the Golden Feather School District.

Wildfire in the Foothills attracted the attention of the U.S. Forest Service, which chose it as one of eight programs in their National Fire Plan study "promoting fire-adapted human communities through youth wildfire education programs" (Ballard and Evans 2012). One of the findings noted in their study was "interactions between parents and students were encouraged by requiring parents to sign exercises brought home and by parents knowing that they would be asked to evaluate the program. All teachers agreed that suggesting students talk with their parents about wildfire would garner little response, so requiring parent acknowledgment of take-home assignments was critical. One teacher . . . told students that he would be talking to their parents about [the program] at teacher-parent conferences, and felt that this was an additional motivation for students to talk with their families. Having multiple checks on accountability were cited as crucial to promoting interaction between students and their family."

Doom the Broom campaign. Scotch, Spanish and French broom, introduced from the Mediterranean for erosion control and ornamental use, have spread to an estimated 600,000 acres in California (McClintock 1985), which is not only a problem that affects plant habitats but a very serious problem in terms of the intensity of wildfires (Downey 2000). As the plant grows, the inner stems die back, providing a highly flammable fuel.

Control efforts were being made by community groups and individuals with little knowledge of the biology of broom plants, which resulted in a high number of projects with limited success. Nader used research information to develop an education program that was integrated into the Butte Fire Safe Council's Doom the Broom campaign. The information was extended through postings on the Web, community meetings and hands-on field training sessions. The key to success is using the right tools at the right time — that is, cutting broom plants when they are under water stress in August, which can cause up to 80% mortality, instead of in the spring, when the plants are not impacted. Since broom seeds can germinate many years after the plants are removed, a list of fire-safe native plants was developed that could be planted to compete with germinating broom plants. After the education, homeowners understood the critical control points of broom control and their efforts were more effective.

Coordinated fire mitigation

After the 1997 Williams fire burned more than 100 homes in Yuba County, the local supervisor called a meeting and said that a fire safe council needed to be formed to make sure this would never happen again. Nader took the lead in forming and managing the council. In 1998, concerns over wildfires in Butte County brought a group of interested parties together and Nader was named chair of the new council there. Both councils were interested in bringing agencies together to plan fire mitigation across the landscape by consensus, rather than according to each agency's jurisdiction, as had been done in the past.

UCCE Advisor Glenn Nader delivers hands-on training to homeowners about the critical points for controlling broom, which is a fire hazard.

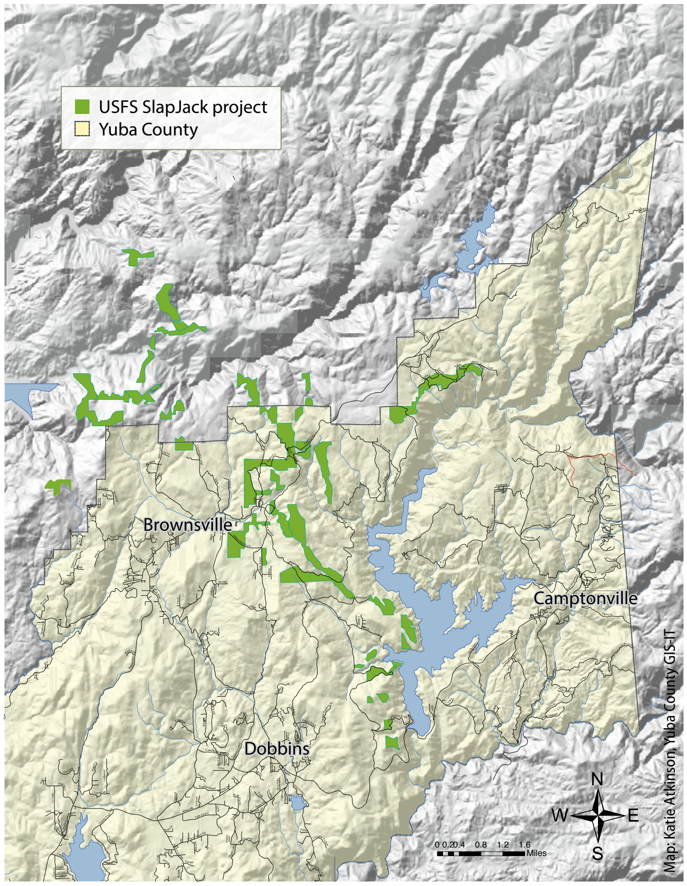

Fig. 5. Map of Slapjack Project, Yuba County.

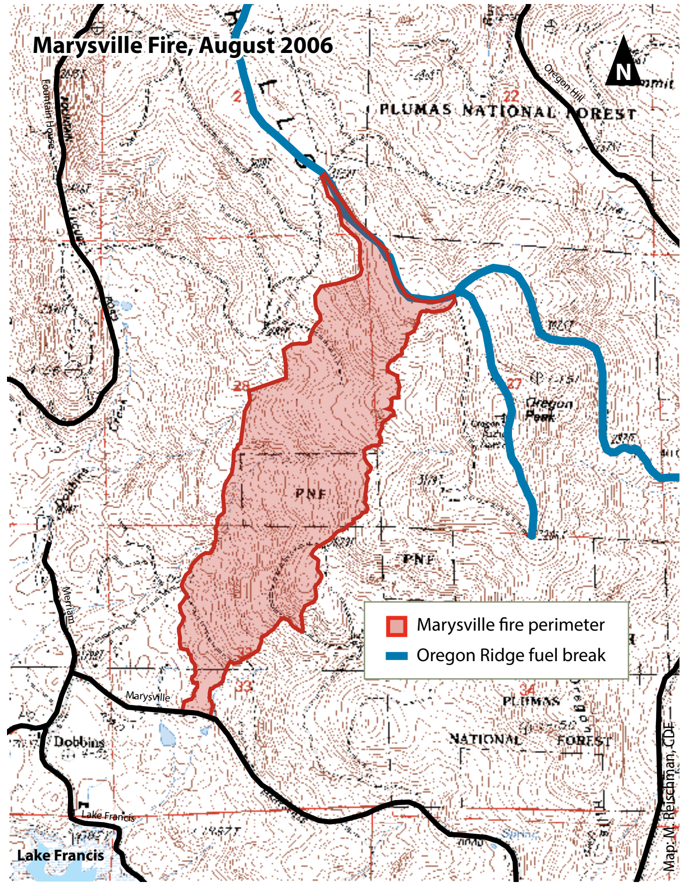

Fig. 6. Map of the Marysville fire.

Nader worked with the Forest Service to form the Slapjack Project in Yuba and Butte counties, which coordinated strategic fuel reduction on 4,419 acres of National Forest, Bureau of Land Management, county and private lands (fig. 5). The Forest Service used Herger Feinstein Quincy Library group funding to implement their portion of the project. De Lasaux provided considerable assistance to the Quincy Library Group as it sought to influence national forest fuel reduction programs. Nader worked with the Yuba Fire Safe Council to obtain $2.8 million in grants to implement the private and county portions of the project. The Slapjack Project played a key role in preventing two fires from becoming catastrophic.

Marysville fire. One part of Slapjack was the construction of the Oregon Ridge fuel break in Yuba County, which was funded by State Water Resources Board Proposition 204 and featured cooperation among private timber landowners CHY, Soper-Wheeler and Siller Brothers. The Marysville fire, which spread over 442 acres in August 2006 (fig. 6), burned to that fuel break and was stopped there. The fuel break provided a relatively safe place for the firefighters to work; and many trees in the break appear to have survived. In this case, coordinated fire prevention activities helped to limit, or prevent, fire damage to homes, trees and watersheds. It was a testament to science-based pre-fire planning with funding for implementation.

The fuel break provided time to marshal firefighting resources. Quick access to the fire was also gained through the new road.

Yuba fire. A California Department of Forestry and Fire Protection Proposition 40 grant to the Yuba Watershed Protection and Fire Safe Council was used by landowner John Middlebrook to construct a fuel break 300 feet wide for 0.75 mile on his property along Marysville Road and 1.1 miles on the eastern boundary of his property. Brush and small trees were masticated with equipment or hand-cut, piled and burned. A maintenance and access road was also constructed. The project was started in 2007 and completed early in 2008.

In August 2009, the Yuba fire consumed 3,891 acres (fig. 7). The fire was slowed down by the south end of the Middlebrook fuel break. If the fire had extended another 500 to 1,000 feet to the north, it would have entered young timber stands, causing considerable economic damage, and spread toward the major county arterial highway, Marysville Road. The fuel break provided time to marshal firefighting resources. Quick access to the fire was also gained through the new road. The $52,500 grant proved to be an investment that paid off many times over in helping to stop the fire.

Fire safe councils and UCCE

The education and applied research activities that have occurred in these wildfire-prone counties illustrate the synergistic relationship between fire safe councils and UCCE. The fire safe councils play a vital role in the communities, alongside federal and state agencies and citizens concerned about forest health and safety. UCCE provides science-based forestry and wildfire information to help the councils fulfill their educational mission and, because of its extensive history in training and collaboration, UCCE presents the information in formats that raise awareness and enable effective pre-fire action. The partnership between the councils and UCCE optimizes the impact that both can have on wildfires in California. CA

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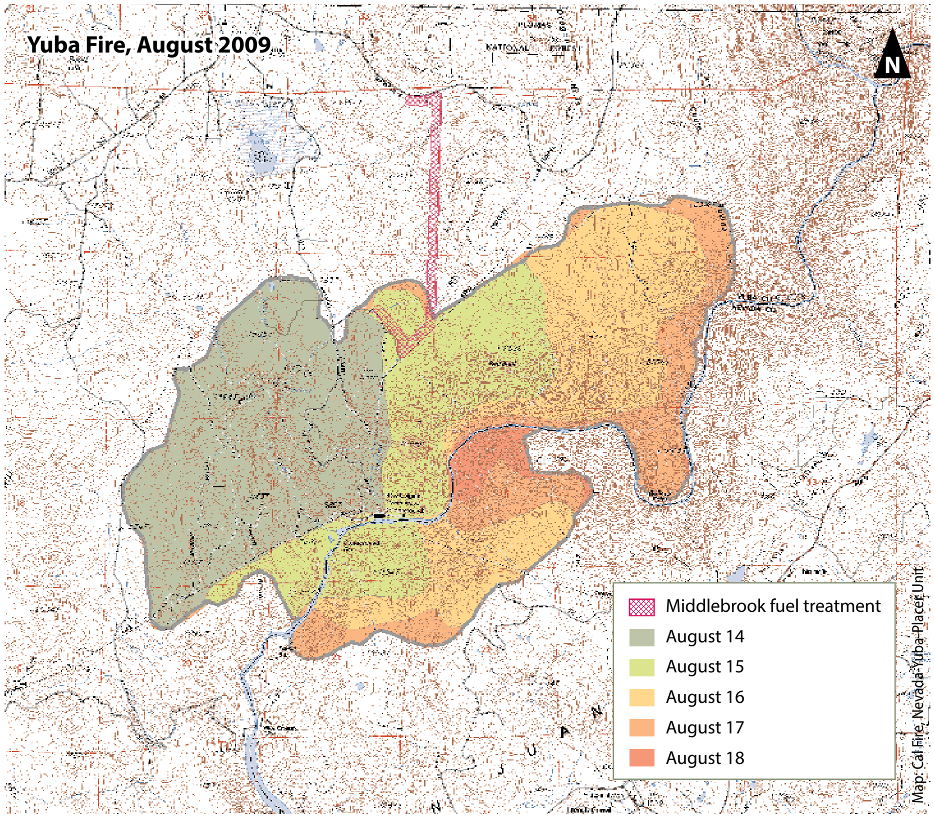

Fig. 7. Map of the Yuba fire.

The Yuba fire stopped at the Middlebrook fuel break and access road.

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